

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
16 January 2003 (16.01.2003)

PCT

(10) International Publication Number
WO 03/005068 A2

- (51) International Patent Classification⁷: **G02B**
- (21) International Application Number: PCT/US02/20817
- (22) International Filing Date: 1 July 2002 (01.07.2002)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
60/302,603 2 July 2001 (02.07.2001) US
- (71) Applicant (for all designated States except US): **OPTICAL POWER SYSTEMS INC.** [US/US]; 86 South Street, Hopkinton, MA 01748 (US).

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

(72) Inventors: and

(75) Inventors/Applicants (for US only): **DEMIDOV, Andrey, A.** [RU/US]; 1110 Franklin Street, Duxbury, MA 02332 (US). **PO, Hong** [US/US]; 8 Towne Lyne Road, Sherborn, MA 01770 (US).

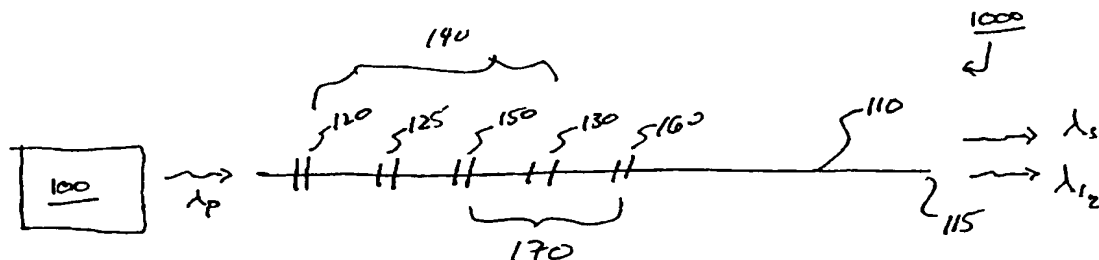
(74) Agent: **DALEY, Sean, P.**; Fish & Richardson P.C., 225 Franklin Street, Boston, MA 02110 (US).

Published:

— without international search report and to be republished upon receipt of that report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: MULTI-WAVELENGTH OPTICAL FIBER



(57) Abstract: Optical fibers (e.g., fiber lasers and fiber amplifiers), and systems containing such optical fibers are disclosed.

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Multi-Wavelength Optical Fiber

TECHNICAL FIELD

This invention relates to optical fibers (e.g., fiber lasers and fiber amplifiers), and systems containing such optical fibers.

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BACKGROUND

Certain optical fibers can be used as fiber amplifiers or fiber lasers.

Fiber amplifiers are typically used to amplify an input signal. Often, the input signal and a pump signal are combined and passed through the fiber amplifier to amplify the signal at the input wavelength. The amplified signal at the input
10 wavelength can then be isolated from the signal at undesired wavelengths.

Raman fiber lasers can be used, for example, as energy sources. In general, Raman fiber lasers include a pump source coupled to a fiber, such as an optical fiber, having a gain medium with a Raman active material. Energy emitted from the pump source at a certain wavelength λ_p , commonly referred to as the pump energy, is coupled
15 into the fiber. As the pump energy interacts with the Raman active material in the gain medium of the fiber, one or more Raman Stokes transitions can occur within the fiber, resulting in the formation of energy within the fiber at wavelengths corresponding to the Raman Stokes shifts that occur (e.g., λ_{s1} , λ_{s2} , λ_{s3} , λ_{s4} , etc.).

Generally, the Raman active material in the gain medium of a Raman fiber laser
20 may have a broad Raman gain spectrum. Usually, conversion efficiency varies for different frequencies within the Raman gain spectrum and many Raman active materials exhibit a peak in their gain spectrum, corresponding to the frequency with highest conversion efficiency. Additionally, the gain spectrum for different Raman active materials may be substantially different, partially overlapping, or of different
25 conversion efficiency.

Typically, a Raman fiber laser is designed so that the energy formed at one or more Raman Stokes shifts is substantially confined within the fiber. This can enhance the formation of energy within the fiber at one or more higher order Raman Stokes shifts. Often, the fiber is also designed so that at least a portion of the energy at
30 wavelengths corresponding to predetermined, higher order Raman Stokes shifts (e.g., λ_{sx}) where x is equal to or greater than one) is allowed to exit the fiber.

SUMMARY

In general, the invention relates to optical fibers (e.g., fiber lasers and fiber amplifiers), and systems containing such optical fibers.

In one aspect, the invention features a fiber that includes an optical fiber
 5 containing a gain medium having a Raman active material with a Raman gain spectrum. The optical fiber is configured to receive energy at a wavelength λ_p . The fiber also includes at least three pairs of reflectors disposed in the optical fiber. Each pair of reflectors forms a resonance cavity with a resonance frequency. Each resonance cavity has an index, and the index of each resonance cavity is different than the index
 10 of the other resonance cavities. For a resonance cavity having an index with a value M (M is an integer having a value of at least one), the resonance cavity has a resonance frequency (c/λ_{sm}) , where $\lambda_{sm}^{-1} = \lambda_p^{-1} - \sum_M \lambda_{rm}^{-1}$, where (c/λ_{rm}) is a frequency within the Raman gain spectrum of the Raman active material contained in the gain medium, and c is the speed of light. For a resonance cavity having an index with a value N, the
 15 resonance cavity has a resonance frequency (c/λ_{sn}) . The resonance cavity having the index value N overlaps only with a resonance cavity having a resonance frequency $(c/\lambda_{s(n-1)})$ and with a resonance cavity having a resonance frequency $(c/\lambda_{s(n+1)})$ (N is an integer having a value of at least two). In the case where N corresponds to the highest index number (i.e., the cavity with the lowest resonance frequency), the cavity overlaps
 20 only with a resonance cavity having a resonance frequency $(c/\lambda_{s(n-1)})$.

For example, $\lambda_{s1}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1}$, where λ_{r1}^{-1} is a frequency in the Raman gain spectrum of the active material. As another example, $\lambda_{s2}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1} - \lambda_{r2}^{-1}$, where λ_{r2}^{-1} is a frequency in the Raman gain spectrum of the active material. As a further example, $\lambda_{s3}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1} - \lambda_{r2}^{-1} - \lambda_{r3}^{-1}$, where λ_{r3}^{-1} is a frequency in the Raman gain
 25 spectrum of the active material. λ_{r1} , λ_{r2} and/or λ_{r3} can be the same or different.

The optical fiber can include, for example, three, four, five, six, seven, eight, nine, 10 or more than 10 pairs of reflectors.

In some embodiments, at least one pair of reflectors has a first reflector and a second reflector. The first reflector is disposed in the optical fiber closer to a point
 30 where energy at the wavelength λ_p enters the optical fiber than the second reflector, and the second reflector is configured to reflect only a portion of energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of

reflectors. The first reflector can be configured to reflect substantially all energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors. The second reflector can be configured to reflect less than about 98% (e.g., less than about 95%, less than about 90%, less than about 75%, less than about 60%, less than about 50%, less than about 25%, less than about 10%) of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors. The amount of energy at the resonance frequency for the resonance cavity that the second reflector is capable of reflecting can be variable.

10 In certain embodiments, each pair of reflectors has a first reflector and a second reflector, and for each pair of reflectors: the first reflector is disposed in the optical fiber closer to a point where energy at the wavelength λ_p enters the optical fiber than the second reflector and the second reflector is configured to reflect only a portion of energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

At least one resonance cavity in the optical fiber can have a suppressor disposed therein. The suppressor can be configured to substantially suppress formation of energy at a frequency (c/λ_x) where $\lambda_x^{-1} = \lambda_z^{-1} - \lambda_a^{-1}$, and (c/λ_z) is the resonance frequency of the resonance cavity and (c/λ_a) is a frequency in the Raman gain spectrum of the active material in the gain medium of the fiber. The suppressor can be, for example, formed of one or more long period gratings.

One pair of reflectors can have first and second reflectors, and the first and second reflectors can be configured to reflect substantially all energy impinging thereon at the resonance frequency of the corresponding resonance cavity.

25 In some embodiments, the at least three pairs of reflectors includes a first pair of reflectors and a second pair of reflectors. The first pair of reflectors has first and second reflectors, and the second pair of reflectors has first and second reflectors. The first and second reflectors of the first pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by first pair of reflectors, and the first and second reflectors of the second pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the second pair of reflectors.

In certain embodiments, the at least three pairs of reflectors includes a first pair of reflectors, a second pair of reflectors and a third pair of reflectors. The first pair of reflectors has first and second reflectors, the second pair of reflectors has first and second reflectors, and the third pair of reflectors has first and second reflectors. The first and second reflectors of the first pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the first pair of reflectors, the first and second reflectors of the second pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the second pair of reflectors, and the first and second reflectors of the third pair of reflectors are configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the third pair of reflectors.

The fiber can further include an additional reflector disposed in the optical fiber. The additional reflector can be configured to at least partially reflect energy impinging thereon (e.g., reflect substantially all energy impinging thereon) at the wavelength λ_p .

One or more of the pairs of reflectors can be formed of a pair of fiber Bragg gratings.

The Raman active material(s) can be, for example, GeO_2 , P_2O_5 , SiO_2 , B_2O_3 or SiO_xF_y .

In another aspect, the fiber can be used in a fiber laser system that also includes an energy source configured to emit energy at a wavelength λ_p .

In a further aspect, the invention features a fiber that includes an optical fiber containing a gain medium having a Raman active material. The optical fiber is configured to receive energy at a wavelength λ_p . The fiber also includes at least three pairs of reflectors disposed in the optical fiber. Each pair of reflectors forms a corresponding resonance cavity with a corresponding resonance frequency. The resonance frequency of each resonance cavity is different than the resonance frequency of any other cavity. The optical fiber is substantially devoid of a portion containing more than two of the resonance cavities. The fiber can be incorporated in a system containing an energy source capable of emitting energy at the wavelength λ_p .

In one aspect, the invention features a fiber that includes an optical fiber containing a plurality of sections including a first section having a gain medium including a first Raman active material and a second section having a gain medium

including a second Raman active material. The second Raman active material can be the same as or different than the first Raman active material. Alternatively, the concentration of the Raman active material in the second section can be the same as or different than the concentration of the Raman active material in the first section of
5 fiber. Or, the diameter of the fiber core of the second section of fiber can be the same as or different than the diameter of the fiber core of the first section of fiber. The optical fiber is configured to receive energy at a wavelength λ_p . At least three pairs of reflectors are disposed in the optical fiber. Each pair of reflectors forms a corresponding resonance cavity with a corresponding resonance frequency. The optical
10 fiber is substantially devoid of a portion containing more than two of the resonance cavities. The fiber can be incorporated in a system that includes an energy source configured to emit energy at a wavelength λ_p .

In another aspect, the invention features a fiber that includes an optical fiber having a gain medium having a Raman active material. The optical fiber is configured
15 to receive energy at a wavelength λ_p . The fiber also includes a plurality of reflectors disposed in the optical fiber. At least some of the plurality of reflectors form resonance cavities in the optical fiber. Each resonance cavity has a resonance frequency. The resonance frequency of each resonance cavity can be different than the resonance frequency of any other cavity. The plurality of reflectors are configured so that when
20 the optical fiber receives energy at the wavelength λ_p , the ratio of the output power at a desired wavelength to the pump power can be at least 20% (e.g., at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 95%, at least 98%) of the theoretical limit.

In a further aspect, the invention features a fiber that includes an optical fiber
25 having a gain medium having a Raman active material. The optical fiber is configured to receive energy at a wavelength λ_p . The fiber also includes a plurality of reflectors disposed in the optical fiber. At least some of the plurality of reflectors form resonance cavities in the optical fiber. Each resonance cavity has a resonance frequency. The resonance frequency of each resonance cavity can be different than the resonance
30 frequency of any other cavity. The plurality of reflectors are configured so that when the optical fiber receives energy at the wavelength λ_p , the ratio of the total output power at one or more desired wavelengths to the pump power can be at least 20% (e.g., at

least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 95%, at least 98%) of the theoretical limit.

In one aspect, the invention features a system that includes a fiber having the structure described herein. The system also includes a splitter configured so that output
5 energy from the fiber can be coupled into the splitter. The system further includes a plurality of optical fibers (e.g., at least five fibers, at least 25 fibers, at least 50 fibers, at least 75 fibers, at least 100 fibers, at least 250 fibers, at least 500 fibers) configured so that energy output from the splitter can be coupled into one or more of the plurality of fibers.

10 In another aspect, the invention features a system that includes a pump laser and a fiber laser coupled to the pump laser so that energy output by the pump laser can be coupled into the fiber laser. The system also includes a fiber as described herein. The fiber is coupled to the fiber laser so that energy output by the fiber laser can be coupled into the fiber. The system can further include an output cascade coupled to the fiber so
15 that energy output by the fiber can be coupled into the output cascade.

In one aspect, the invention features a fiber that includes an optical fiber containing a gain medium having a Raman active material with a Raman gain spectrum. The optical fiber is configured to receive energy at a wavelength λ_p . The fiber also includes at least three pairs of reflectors disposed in the optical fiber. Each
20 pair of reflectors forms a resonance cavity with a resonance frequency. Each resonance cavity has an index, and the index of each resonance cavity is different than the index of the other resonance cavities. For a resonance cavity having an index with a value M (M is an integer having a value of at least one), the resonance cavity has a resonance frequency (c/λ_{sm}) , where $\lambda_{sm}^{-1} = \lambda_p^{-1} - \sum_M \lambda_{rm}^{-1}$, where (c/λ_{rm}) is a frequency within the
25 Raman gain spectrum of the Raman active material contained in the gain medium, and c is the speed of light. For a resonance cavity having an index with a value N, the resonance cavity has a resonance frequency (c/λ_{sn}) . and the reflectors are configured so that at least two resonance cavities do not overlap. In another aspect, the invention features a system including an energy source coupled to such a fiber.

30 In some embodiments, the invention can provide a Raman fiber laser having a relatively high output power at one or more desired wavelengths relative to the power of the pump laser that is received by the fiber (e.g., at the wavelength λ_p). For example,

the ratio of the output power at one or more desired wavelengths to the pump power can be at least 20% (e.g., at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 95%, at least 98%) of the theoretical limit.

As used herein, the theoretical limit of the ratio of the output power at a desired
 5 wavelength λ_x to the pump power (λ_p) is the ratio of the wavelength of λ_p to the wavelength of λ_x , when optical losses are neglected.

As used herein, the theoretical limit of the ratio of the total output power at one or more desired wavelengths (e.g., λ_x , λ_y , λ_z) to the pump power λ_p is the sum of the individual ratios the wavelength of λ_p to the desired wavelength(s) (e.g., λ_p/λ_x , λ_p/λ_y ,
 10 λ_p/λ_z , respectively).

In some embodiments, the input power can be at least about 0.1 Watt (e.g., at least about 0.5 Watt, at least about one Watt, at least about 2 Watts, at least about 5 Watts, at least about 10 Watts).

In certain embodiments, the output power at a desired wavelength can be at
 15 least about 0.1 Watt (e.g., at least about 0.5 Watt, at least about one Watt, at least about 2 Watts, at least about 5 Watts, at least about 10 Watts).

In certain embodiments, the total output power at one or more desired wavelengths can be at least about 0.1 Watt (e.g., at least about 0.5 Watt, at least about one Watt, at least about 2 Watts, at least about 5 Watts, at least about 10 Watts).

20 In some embodiments, the output power at one or more undesired wavelengths can be relatively low (e.g., less than about one Watt, less than about 0.5 Watt, less than about 0.1 Watt, less than about 0.05 Watt).

In certain embodiments, it is a feature of the invention that λ_p pumps only λ_{s1} .

In some embodiments, it is a feature of the invention that energy at a given
 25 Stokes shift frequency is pumped only by one other Stokes shift frequency.

In certain embodiments, the fibers can be used as amplifiers rather than lasers.

Features, objects and advantages of the invention are in the description, drawings and claims.

DESCRIPTION OF DRAWINGS

30 Fig. 1 is a schematic representation of an embodiment of a Raman fiber laser system;

Figs. 2 is a plot of output energy intensity as a function of pump energy intensity for embodiments of a Raman fiber laser;

Fig. 3 is a schematic representation of an embodiment of a Raman fiber laser system;

5 Fig. 4 is a schematic representation of an embodiment of a Raman fiber laser system;

Fig. 5 is a schematic representation of an embodiment of a Raman fiber laser system;

10 Fig. 6 is a schematic representation of an embodiment of a Raman fiber laser system;

Fig. 7 is a schematic representation of an embodiment of a Raman fiber laser system;

Fig. 8 is a schematic representation of an embodiment of a fiber amplifier system;

Fig. 9 is a schematic representation of an embodiment of a fiber amplifier system;

Fig. 10 is a schematic representation of an embodiment of a fiber laser system;

Fig. 11 is a schematic representation of an embodiment of a fiber amplifier system; and

Fig. 12 is a schematic representation of an embodiment of a Raman fiber laser system.

Like reference symbols in the various drawings indicate like elements.

DETAILED DESCRIPTION

25 Fig. 1 shows an embodiment of a Raman fiber laser system 1000 including a laser 100 and an optical fiber 110. Laser 100 is configured so that energy emitted by laser 100 at a wavelength λ_p is coupled into optical fiber 110. Optical fiber 110 has a gain medium containing a Raman active material. Examples of Raman active materials include GeO_2 , P_2O_5 , SiO_2 , B_2O_3 , SiO_xF_y , and the like.

30 Optical fiber 110 includes a first pair of reflectors 120 and 130 (e.g., a pair of fiber Bragg gratings). Reflector 120 is configured to reflect substantially all (e.g., about 100 %) energy impinging thereon at a wavelength λ_{s1} , where $\lambda_{s1}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1}$,

where (c/λ_{r1}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in the gain medium of fiber 110, and c is the speed of light.

Reflector 130 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than
5 about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength λ_{s1} . Reflectors 120 and 130 form a resonance cavity 140 in fiber 110 for energy at wavelength λ_{s1} .

Optical fiber 110 also includes a reflector 125 that is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength λ_p .

10 Optical fiber 110 further includes a second pair of reflectors 150 and 160 (e.g., a pair of fiber Bragg gratings). Reflector 150 is configured to reflect substantially all (e.g., about 100 %) energy impinging thereon at a wavelength λ_{s2} , where $\lambda_{s2}^{-1} = \lambda_{s1}^{-1} - \lambda_{r2}^{-1}$, where (c/λ_{r2}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in the gain medium of fiber 110 (λ_{r2}^{-1} may be the same as
15 or different from λ_{r1}^{-1}). Reflector 160 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength λ_{s2} .

Reflectors 150 and 160 form a resonance cavity 170 in fiber 110 for energy at
20 wavelength λ_{s2} . In certain embodiments, reflector 125 is relatively close to reflector 150. In some embodiments, reflector 150 can be in cavity 170.

With this arrangement, as energy at λ_p enters optical fiber 110, the energy at λ_p propagates through fiber 110 and impinges upon reflector 125 where it is reflected and propagates in fiber 110 in the reverse direction. As energy at λ_p propagates through
25 fiber 110, it interacts with the Raman active material in the gain medium of fiber 110 to create energy at wavelength λ_{s1} . Energy at λ_{s1} in cavity 140 that is propagating in the forward direction impinges upon reflector 130. A portion of the energy at λ_{s1} that impinges on reflector 130 is reflected backward, and a portion of the energy at λ_{s1} that impinges on reflector 130 continues to propagate through fiber 110 in the forward
30 direction and exits fiber 110 (e.g., at an end 115 of fiber 110). The portion of energy at λ_{s1} that is reflected by reflector 130 propagates through fiber 110 in the reverse direction until it reaches reflector 120 where it is reflected and then propagates through

fiber 110 in the forward direction. Some of the energy at wavelength λ_{s1} continues to propagate in fiber 110 in the forward and in reverse directions in resonance cavity 140, and some of the energy at wavelength λ_{s1} exits resonance cavity 140 through reflector 130 and ultimately exits fiber 110 (e.g., at end 115).

5 As energy at wavelength λ_{s1} propagates through fiber 110, it interacts with the Raman active material in the gain medium of fiber 110 to create energy at wavelength λ_{s2} . Energy at wavelength λ_{s2} in cavity 170 that is propagating in the reverse direction is reflected by reflector 150 and then propagates through fiber 110 in the forward direction. Energy at wavelength λ_{s2} propagating in cavity 170 in the forward direction
10 impinges on reflector 160. Some of the energy at λ_{s2} impinging on reflector 160 is reflected by reflector 160 and then propagates through cavity 170 in the reverse direction, and some of the energy at λ_{s2} impinging on reflector 160 passes through reflector 160 and exits fiber 110 (e.g., at end 115). It is to be noted that, in this embodiment, λ_p does not directly pump λ_{s2} .

15 Resonance cavities 110 and 140 are linked resonance cavities because, while a portion of these cavities overlaps, a portion of the cavities does not overlap.

Without wishing to be bound by theory, it is believed that this design can allow for enhanced control of the intensity of energy output by fiber 110 at wavelengths λ_{s1} and λ_{s2} by controlling (e.g., independently controlling) the transmission of reflectors
20 130 and/or 160, and/or the intensity of the pump energy. For the case where reflector 130 is positioned close to reflector 160 (i.e., $z_{125} \approx z_{150}$ and $z_{130} \approx z_{160}$, where z_x is to the position of reflector x), it is believed that the performance of fiber 110 can be explained, at least in part, using the following system of equations.

$$\begin{aligned}
 & \left. \begin{aligned} \frac{dI_p^+}{dz} &= -g_p(I_{\lambda_{s1}}^+ + I_{\lambda_{s1}}^-) \times I_p^+ - \alpha_p I_p^+ = -\frac{dI_p^-}{dz} \\ \frac{dI_{\lambda_{s1}}^+}{dz} &= g_1 I_{\lambda_{s1}}^+ \times (I_p^+ + I_p^-) - \alpha_1 I_{\lambda_{s1}}^+ = -\frac{dI_{\lambda_{s1}}^-}{dz} \end{aligned} \right\} \text{.....Along cavity 140} \\
 & \left. \begin{aligned} \frac{dI_{\lambda_{s1}}^+}{dz} &= -\tilde{g}_1 I_{\lambda_{s1}}^+ \times (I_{\lambda_{s2}}^+ + I_{\lambda_{s2}}^-) - \alpha_1 I_{\lambda_{s1}}^+ = -\frac{dI_{\lambda_{s1}}^-}{dz} \\ \frac{dI_{\lambda_{s2}}^+}{dz} &= g_2 I_{\lambda_{s2}}^+ \times (I_{\lambda_{s1}}^+ + I_{\lambda_{s1}}^-) - \alpha_2 I_{\lambda_{s2}}^+ = -\frac{dI_{\lambda_{s2}}^-}{dz} \end{aligned} \right\} \text{.....Along cavity 170}
 \end{aligned}$$

with the boundary conditions:

$$I_p^+(z=0) = I_0; \quad I_p^-(z=z_{125}) = R_p \times I_p^+(z=z_{125});$$

$$I_{\lambda_{s1}}^+(z=z_{120}) = R_{\lambda_{s1}}^{120} \times I_{\lambda_{s1}}^-(z=z_{120}), \quad I_{\lambda_{s1}}^-(z=z_{130}) = R_{\lambda_{s1}}^{130} \times I_{\lambda_{s1}}^+(z=z_{130});$$

$$I_{\lambda_{s2}}^+(z=z_{150}) = R_{\lambda_{s2}}^{150} \times I_{\lambda_{s2}}^-(z=z_{150}), \quad I_{\lambda_{s2}}^-(z=z_{160}) = R_{\lambda_{s2}}^{160} \times I_{\lambda_{s2}}^+(z=z_{160});$$

- 5 The indices $^+$ and $^-$ represent propagation in fiber 110 from left to right and from right to left, respectively. $I_p, I_{\lambda_{s1}}$, and $I_{\lambda_{s2}}$ represent the intensities of energy propagating in fiber 110 at wavelengths λ_p, λ_{s1} and λ_{s2} , respectively. α_p, α_1 and α_2 are the loss coefficients of energy propagating in fiber 110 at wavelengths λ_p, λ_{s1} and λ_{s2} , respectively, due to, for example, imperfections, scattering and/or splicing in fiber 110.
- 10 g_p, g_1, \tilde{g}_1 and g_2 are the Raman gain coefficients, respectively, of energy propagating in fiber 110 at wavelengths λ_p, λ_{s1} and λ_{s2} , respectively, due to stimulated Raman scattering (SRS). It is to be noted that g_1 and \tilde{g}_1 represent gain coefficients for energy at λ_{s1} which can correspond to the same or different portion(s) of the Raman gain spectrum of the Raman active material in the gain medium of fiber 110. g_1 ,
- 15 corresponds to SRS energy transfer from λ_p to λ_{s1} , and \tilde{g}_1 corresponds to SRS energy transfer from λ_{s1} to λ_{s2} , with respect to λ_{s1} . g_2 is the Raman gain coefficient for the transfer of energy from λ_{s1} to λ_{s2} , with respect to λ_{s2} , and is defined by $g_2 = (\lambda_{s2}/\lambda_{s1})(\tilde{g}_1)$. Additionally, in the boundary conditions, and $R_{\lambda_{sy}}^x$ is the reflectance of reflector x at wavelength λ_{sy} , where reflectance is the ratio between reflected and incident
- 20 intensity.

Based on these equations, it is believed that after reaching generation threshold the intensity of energy output by fiber 110 at wavelength λ_{s1} increases monotonically as the intensity of energy at wavelength λ_p input into fiber 110 is increased until the intensity of energy at λ_p reaches a value I_{crit} . Below I_{crit} , the intensity of energy output by fiber 110 at wavelength λ_{s2} is about zero. Above I_{crit} , the intensity of energy output by fiber 110 at wavelength λ_{s2} increases monotonically while the energy output by fiber 110 at wavelength λ_{s1} remains substantially constant. The particular value I_{crit} depends, at least in part, upon the transmission of reflectors 130 and 160.

Fig. 2 shows the calculated output intensities for fiber 110 for system 1000 as a function of the intensity of the pump energy (λ_p) where the reflectance of reflector 130 for energy impinging thereon at wavelength λ_{s1} is varied (20%, 30%, 40%, 50%, 60%,

70%, 80%, 90%) and where reflector 160 reflects 50% of energy impinging thereon at wavelength λ_{s2} . In this example, λ_{s2} is 1480 nm, λ_{s1} is 1455nm, and fiber 110 is formed of fused silica with GeO_2 as the Raman active material.

Fig. 3 shows a Raman fiber laser system 2000 in which fiber 110 includes
 5 reflector 125 and pairs of reflectors 120 and 130, and 150 and 160. Fiber 110 also includes a pair of reflectors 200 and 210. Reflector 200 is configured to reflect substantially all (e.g., about 100 %) energy impinging thereon at a wavelength λ_{s3} , where $\lambda_{s3}^{-1} = \lambda_{s2}^{-1} - \lambda_{r3}^{-1}$, where (c/λ_{r3}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in the gain medium of fiber 110
 10 $(\lambda_{r3}^{-1}$ may be the same as or different from λ_{r2}^{-1} and/or $\lambda_{r1}^{-1})$. Reflector 210 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength λ_{s3} . Reflectors 200 and 210 form a resonance cavity
 15 220 in fiber 110 for energy at wavelength λ_{s3} .

With this arrangement, energy at wavelength λ_p generally propagates in fiber 110 as described above. In addition, energy at wavelengths λ_{s1} and λ_{s2} generally is formed and propagates in fiber 110 as described above. As energy at wavelength λ_{s2} propagates through fiber 110 (e.g., in the overlapping region of cavities 170 and 220), it
 20 interacts with the Raman active material in the gain medium of fiber 110 to create energy at wavelength λ_{s3} . Energy at wavelength λ_{s3} in cavity 220 that is propagating in the reverse direction is reflected by reflector 200 and then propagates through fiber 110 in the forward direction. Energy at wavelength λ_{s3} propagating in cavity 220 in the forward direction impinges on reflector 210. Some of the energy at λ_{s3} impinging on
 25 reflector 210 is reflected by reflector 210 and then propagates through cavity 220 in the reverse direction, and some of the energy at λ_{s3} impinging on reflector 210 passes through reflector 210 and exits fiber 110 (e.g., at end 115). It is to be noted that, in this embodiment, λ_p directly pumps only λ_{s1} , λ_{s2} is directly pumped by only λ_{s1} , and that λ_{s3} is directly pumped only by λ_{s2} .

30 Resonance cavities 140 and 170 are linked resonance cavities, and resonance cavities 170 and 220 are linked resonance cavities.

Fig. 4 shows a Raman fiber laser system 3000 in which fiber 110 includes reflector 125 and pairs of reflectors 120 and 130, 150 and 160, and 200 and 210. Fiber

110 also includes a pair of reflectors 300 and 310. Reflector 300 is configured to reflect substantially all (e.g., about 100 %) energy impinging thereon at a wavelength λ_{s4} , where $\lambda_{s4}^{-1} = \lambda_{s3}^{-1} - \lambda_{r4}^{-1}$, where (c/λ_{r4}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in the gain medium of fiber 110 (λ_{r4}^{-1} may be the same as or different from λ_{r3}^{-1} , λ_{r2}^{-1} and/or λ_{r1}^{-1}). Reflector 310 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength λ_{s4} . Reflectors 300 and 310 form a resonance cavity 320 in fiber 110 for energy at wavelength λ_{s4} .

With this arrangement, energy at wavelength λ_p generally propagates in fiber 110 as described above. In addition, energy at wavelengths λ_{s1} , λ_{s2} and λ_{s3} generally is formed and propagates in fiber 110 as described above. As energy at wavelength λ_{s3} propagates through fiber 110 (e.g., in the overlapping region of cavities 220 and 320), it interacts with the Raman active material in the gain medium of fiber 110 to create energy at wavelength λ_{s4} . Energy at wavelength λ_{s4} in cavity 320 that is propagating in the reverse direction is reflected by reflector 300 and then propagates through fiber 110 in the forward direction. Energy at wavelength λ_{s4} propagating in cavity 320 in the forward direction impinges on reflector 310. Some of the energy at λ_{s4} impinging on reflector 310 is reflected by reflector 310 and then propagates through cavity 320 in the reverse direction, and some of the energy at λ_{s4} impinging on reflector 310 passes through reflector 310 and exits fiber 110 (e.g., at end 115). It is to be noted that, in this embodiment, λ_p directly pumps only λ_{s1} , λ_{s2} is directly pumped by only λ_{s1} , λ_{s3} is directly pumped only by λ_{s2} , and λ_{s4} is directly pumped only by λ_{s3} .

Resonance cavities 140 and 170 are linked cavities, resonance cavities 170 and 220 are linked cavities, and resonance cavities 170 and 220 are linked cavities.

While the foregoing description has been made for a system containing two, three or four pairs of reflectors, the invention is not limited in this manner. Rather, the number of pairs of reflectors can be greater than two (e.g., five pairs of reflectors, six pairs of reflectors, seven pairs of reflectors, eight pairs of reflectors, nine pairs of reflectors, 10 pairs of reflectors, etc.). In general, the pairs of reflectors are arranged so

that each pair of reflectors forms a resonance cavity at a respective wavelength corresponding to a Raman Stokes shift. Typically, each pair of reflectors includes one reflector that reflects substantially all (e.g., about 100%) energy at the Raman Stokes shift wavelength (e.g., disposed closer to the point of the optical fiber where the pump energy enters the fiber) and one reflector that partially reflects energy at the Raman Stokes shift wavelength (e.g., disposed further from the point of the optical fiber where the pump energy enters the fiber). Usually, the resonance cavities are arranged so that the resonance cavity for energy at the wavelength λ_{sn} overlaps only with a maximum of two resonance cavities. One of the two resonance cavities is for energy at the wavelength λ_{sn-1} , where $\lambda_{sn-1}^{-1} = \lambda_{sn}^{-1} + \lambda_m^{-1}$ and the other of the two resonance cavities is for energy at the wavelength λ_{sn+1} , where $\lambda_{sn+1}^{-1} = \lambda_{sn}^{-1} - \lambda_{m+1}^{-1}$ (λ_m^{-1} and λ_{m+1}^{-1} being Stokes shifts within the Raman gain spectrum of the active material in the gain medium of fiber 110; λ_m^{-1} and λ_{m+1}^{-1} being the same or different). Generally, relative to the resonance cavity for energy at wavelength λ_{sn} , the resonance cavity for energy at λ_{sn-1} is closer to the portion of fiber 110 where the energy at wavelength λ_p enters fiber 110, and the resonance cavity for energy at λ_{sn+1} is further from the portion of fiber 110 where the energy at wavelength λ_p enters fiber 110. Typically, the resonance cavity having a resonance frequency closest to λ_p^{-1} overlaps with only one other resonance cavity, and the resonance cavity having a resonance frequency furthest from λ_p^{-1} overlaps with only one other resonance cavity.

Although systems have been described in which each resonance cavity is formed of a pair of reflectors with one reflector that only partially reflects energy at the corresponding wavelength of the resonance cavity, the invention is not limited in this sense. In certain embodiments, one or more of the pairs of reflectors can have both reflectors that only partially reflect energy at the corresponding wavelength of the resonance cavity. In some embodiments, one or more of the pairs of reflectors can have both reflectors that reflect substantially (e.g., about 100%) the energy at the corresponding wavelength of the resonance cavity.

Moreover, the invention is not limited to systems in which the reflectance of a reflector is fixed. In some embodiments, the reflectance of a reflector can be variable. For example, the amount of energy reflected of reflectors 130, 160, 210, and/or 310 at their respective corresponding wavelengths can be variable. In certain embodiments,

the amount of energy reflected of reflectors 120, 150, 200, and/or 300 at their respective corresponding wavelengths can be variable. Various combinations of tunable reflectors are contemplated. Furthermore, these systems can include, for example, appropriate electronics to form a feedback loop so that the systems can
5 monitor the intensity of energy output at one or more wavelengths and vary the reflectance of one or more reflectors (e.g., vary the reflectance of one or more reflectors in real time) to obtain one or more desired output intensities at one or more wavelengths.

In certain embodiments, a reflector can be formed of a variable output coupler.
10 Such couplers are described, for example, in commonly owned P.C.T. Patent Application Serial _____, filed on June 19, 2002, and entitled "Apparatus and Method for Variable Optical Output Control," which is hereby incorporated by reference.

In addition, one or more of the resonance cavities contained within a Raman
15 fiber laser system can contain a suppressor that is designed to substantially reduce (e.g., substantially eliminate) the formation of unwanted energy in the resonance cavity or cavities. Typically, such unwanted energy corresponds to energy at higher order Stokes shifts than the resonance energy for the resonance cavity. The suppressor can be, for example, a long period grating having a resonance frequency corresponding to the
20 frequency of the undesired energy.

In some embodiments, an optical fiber can be formed of more than one segment of fiber coupled together. For example, Fig. 5 shows a Raman fiber laser system 7000 including laser 100 and an optical fiber 705. Optical fiber 705 has a first section 720 with a gain medium containing a Raman active material and a second section 730 with
25 a gain medium containing a Raman active material. Sections 720 and 730 are coupled together at point 710 (e.g., spliced together). The Raman active material of the gain medium in section 720 may be the same as or different from the Raman active material of the gain medium in section 730. In some embodiments, sections 720 and 730 may have the same Raman active material in their respective gain media, but the
30 concentration of the Raman active material in section 720 is different than the concentration of the Raman active material in section 730. In certain embodiments, sections 720 and 730 may have the same Raman active material in their respective gain media, but the radius of the portion of section 720 that contains the Raman active

material is different than the radius of the portion of section 730 that contains the Raman active material in section 730. Various combinations of active material, radius and active material concentration in segments 720 and 730, respectively, can be used.

It is to be noted that in embodiments where sections 720 and 730 contain the same

- 5 Raman active material having the same concentration and radius, the position of splice point 710 can have substantially no impact on the performance of system 7000.

Optical fiber 705 includes reflector 125, and pairs of reflectors 725 and 735 forming resonance cavity 740. Reflector 725 is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength λ_{s1} , where $\lambda_{s1}^{-1} = \lambda_p^{-1} - \lambda_{r1}^{-1}$

- 10 and (c/λ_{r1}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in section 720. Reflector 735 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at

- 15 wavelength λ_{s1} . Reflectors 725 and 735 form a resonance cavity 740 in fiber 705 for energy at wavelength λ_{s1} . A portion of resonance cavity 740 is in section 720 of fiber 705, and a portion of resonance cavity 740 is in section 730 of fiber 705.

Fiber 705 further includes a pair of reflectors 750 and 760. Reflector 750 is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength λ_{s1} , where $\lambda_{s1}^{-1} = \lambda_{s1}^{-1} - \lambda_{r1}^{-1}$ and (c/λ_{r1}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in section 730. Reflector 760 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of

25 energy impinging thereon at wavelength λ_{s1} . Reflectors 750 and 760 form a resonance cavity 770 in fiber 705 for energy at wavelength λ_{s1} .

- With this arrangement, energy at wavelength λ_p enters optical fiber 705 in section 720. The energy at λ_p propagates through section 720 of fiber 705 and impinges upon reflector 125 where it is reflected and propagates in section 720 of fiber 705 in the
- 30 reverse direction. As energy at λ_p propagates through section 720 of fiber 705 it interacts with the Raman active material in the gain medium of section 720 of fiber 705 to create energy at wavelength λ_{s1} . Energy at λ_{s1} in cavity 740 that is propagating in the

forward direction can propagate in the gain medium of sections 720 and 730 prior to impinging upon reflector 735. A portion of the energy at λ_{s1} that impinges on reflector 735 continues to propagate to propagate through fiber 705 in the forward direction and exits fiber 705 (e.g., at an end 715 of fiber 705). The portion of energy at λ_{s1} that is
 5 reflected by reflector 735 can propagate in sections 720 and 730 of fiber 705 in the reverse direction until it reaches reflector 725 where it is reflected and propagates through fiber 705 in the forward direction within cavity 740.

As energy at λ_{s1} propagates in section 730 of fiber 705 (e.g., between splice point 710 and reflector 735), it can interact with the Raman active material of the gain
 10 medium of section 730 to create energy at wavelength $\lambda_{s1'}$. Energy at wavelength $\lambda_{s1'}$ in cavity 770 that is propagating in the reverse direction is reflected by reflector 750 and then propagates through fiber 705 in the forward direction. Energy at wavelength $\lambda_{s1'}$ propagating in cavity 770 in the forward direction impinges on reflector 760. Some of the energy impinging on reflector 760 is reflected by reflector 760 and then propagates
 15 through cavity 770 in the reverse direction, and some energy at $\lambda_{s1'}$ impinging on reflector 760 passes through reflector 760 and exits fiber 705 (e.g., at end 715). It is to be noted that, in this embodiment, λ_p directly pumps only λ_{s1} , and that $\lambda_{s1'}$ is directly pumped only by λ_{s1} . The order of the reflectors, however, can be varied. For example, reflector 760 can be located to the left of reflector 735, or the right side of splice point
 20 710, or the like.

Resonance cavities 740 and 770 are linked cavities.

Without wishing to be bound by theory, it is believed that this design can allow for enhanced control of the intensity of energy output by fiber 705 at wavelengths λ_{s1} and $\lambda_{s1'}$ by controlling (e.g., independently controlling) the transmission of reflectors
 25 735 and/or 760, and/or the intensity of the pump energy. It is believed that the performance of fiber 705, in the case where reflector 735 is positioned in close proximity to reflector 760 (i.e., $z_{125} \approx z_{750} \approx z_{710}$ and $z_{735} \approx z_{760}$), can be explained, at least in part, using the following system of equations.

$$\frac{dI_p^+}{dz} = -g_p (I_{\lambda_{s1}}^+ + I_{\lambda_{s1}}^-) \times I_p^+ - \alpha_p I_p^+ = -\frac{dI_p^-}{dz}$$

$$\frac{d\hat{I}_{\lambda_{s1}}^+}{dz} = g_1 \hat{I}_{\lambda_{s1}}^+ \times (I_p^+ + I_p^-) - \alpha_1 \hat{I}_{\lambda_{s1}}^+ = -\frac{d\hat{I}_{\lambda_{s1}}^-}{dz}$$

$$\frac{d\tilde{I}_{\lambda_{s1}}^+}{dz} = -\tilde{g}_1 \tilde{I}_{\lambda_{s1}}^+ \times (I_{\lambda_{s1'}}^+ + I_{\lambda_{s1'}}^-) - \tilde{\alpha}_1 I_{\lambda_{s1}}^+ = -\frac{d\tilde{I}_{\lambda_{s1}}^-}{dz}$$

$$\frac{dI_{\lambda_{s1'}}^+}{dz} = g_{1'} I_{\lambda_{s1'}}^+ \times (\tilde{I}_{\lambda_{s1}}^+ + \tilde{I}_{\lambda_{s1}}^-) - \alpha_{1'} I_{\lambda_{s1'}}^+ = -\frac{dI_{\lambda_{s1'}}^-}{dz}$$

The indices $^+$ and $^-$ represent propagation in fiber 705 from left to right and from
 5 right to left, respectively. I_p , $I_{\lambda_{s1}}$, and $I_{\lambda_{s1'}}$ represent the intensities of energy
 propagating in fiber 705 at wavelengths λ_p , λ_{s1} and $\lambda_{s1'}$, respectively. α_p , $\alpha_{1'}$ are the loss
 coefficients of energy propagating in fiber 705 at wavelengths λ_p and $\lambda_{s1'}$, respectively,
 due to, for example, imperfections, scattering and/or splicing in fiber 705. α_1 and $\tilde{\alpha}_1$
 are loss coefficients for sections 720 and 730, respectively, for energy at wavelength λ_{s1}
 10 (e.g., due to imperfections, scattering and/or splicing). g_p and $g_{1'}$ are the Raman gain
 coefficients for energy propagating in fiber 705 at wavelengths λ_p and $\lambda_{s1'}$, respectively,
 due to power gain from stimulated Raman scattering (SRS). g_1 , \tilde{g}_1 are Raman gain
 coefficients for energy propagating in sections 720 and 730, respectively, at λ_{s1} due to
 power gain from stimulated Raman scattering (SRS). $g_{1'} = (\lambda_{s1}/\lambda_{s1})(\tilde{g}_1)$.

15

The boundary conditions at the reflectors and splice point are given by:

$$I_p^+(z=0) = I_0; I_p^-(z=z_{125}) = R_{\lambda_p}^{125} \times I_p^+(z=z_{125});$$

$$\hat{I}_{\lambda_{s1}}^+(z=z_s) = \tilde{I}_{\lambda_{s1}}^+(z=z_s); \hat{I}_{\lambda_{s1}}^-(z=z_s) = \tilde{I}_{\lambda_{s1}}^-(z=z_s);$$

$$\hat{I}_{\lambda_{s1}}^+(z=z_{725}) = R_{\lambda_{s1}}^{725} \times \hat{I}_{\lambda_{s1}}^-(z=z_{725}); \tilde{I}_{\lambda_{s1}}^-(z=z_{735}) = R_{\lambda_{s1}}^{735} \times \tilde{I}_{\lambda_{s1}}^+(z=z_{735});$$

20

$$I_{\lambda_{s1'}}^+(z=z_{750}) = R_{\lambda_{s1'}}^{750} \times I_{\lambda_{s1}}^-(z=z_{750}); I_{\lambda_{s1'}}^-(z=z_{760}) = R_{\lambda_{s1'}}^{760} \times I_{\lambda_{s1'}}^+(z=z_{760});$$

Here z_s is the splice point of two fibers, and z_x and $R_{\lambda_{s1}}^x$ are as defined above. I_0
 is the total pump power.

Fig. 6 shows a Raman fiber laser system 8000 including laser 100 and optical fiber 705 with sections 720 and 730 coupled at point 710. Fiber 705 includes reflector 125, and pairs of reflectors 725 and 735, and 750 and 760, forming resonance cavities 740 and 770, respectively. Fiber 110 also includes a pair of reflectors 850 and 860 (e.g., fiber Bragg gratings). Reflector 850 is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength λ_{s2}' where $\lambda_{s2}'^{-1} = \lambda_{s1}'^{-1} - \lambda_{r2}'^{-1}$, and (c/λ_{r2}') is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in section 730 ($\lambda_{r2}'^{-1}$ can be the same as or different from $\lambda_{r1}'^{-1}$). Reflector 860 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength λ_{s2}' . Reflectors 850 and 860 form a resonance cavity 870 in fiber 705 for energy at wavelength λ_{s2}' .

With this arrangement, energy at λ_p generally propagates in fiber 705 as described above. In addition energy at wavelengths λ_{s1} and λ_{s1}' generally is formed and propagates through fiber 705 as described above. As energy at wavelength λ_{s1}' propagates through section 730 of fiber 705 (e.g., in the region overlapping cavities 770 and 870), it interacts with the Raman active material of section 730 of fiber 705 to create energy at wavelength λ_{s2}' . Energy at wavelength λ_{s2}' in cavity 870 that is propagating in the reverse direction is reflected by reflector 850 and then it propagates through fiber 705 in the forward direction. Energy at wavelength λ_{s2}' propagating in cavity 870 in the forward direction impinges on reflector 860. Some of the energy at λ_{s2}' impinging on reflector 860 is reflected by reflector 860 and then propagates through cavity 870 in the reverse direction, and some of the energy at λ_{s2}' impinging on reflector 860 passes through reflector 860 and exits fiber 705 (e.g., at end 715). It is to be noted that, in this embodiment, λ_p directly pumps only λ_{s1} , λ_{s1}' is directly pumped only by λ_{s1} , and λ_{s2}' is directly pumped only by λ_{s1}' .

Resonance cavities 740 and 770 are linked cavities, and resonance cavities 770 and 870 are linked cavities.

Fig. 7 shows a Raman fiber laser system 9000 including laser 100 and optical fiber 705 with sections 720 and 730 coupled at point 710. Fiber 705 includes reflector 125, and pairs of reflectors 725 and 735, 750 and 760, and 850 and 860, forming

resonance cavities 740, 770 and 870, respectively. Fiber 705 also includes a pair of reflectors 950 and 960 (e.g., fiber Bragg gratings). Reflector 950 is configured to reflect substantially all (e.g., about 100%) energy impinging thereon at wavelength λ_{s3} , where $\lambda_{s3}^{-1} = \lambda_{s2}^{-1} - \lambda_{r3}^{-1}$, and (c/λ_{r3}) is a Raman Stokes shift frequency within the Raman gain spectrum of the Raman active material in section 730 (λ_{r3}^{-1} can be the same as or different than λ_{r1}^{-1} and/or λ_{r2}^{-1}). Reflector 960 is configured to reflect a portion (e.g., less than about 98%, less than about 95%, less than about 90%, less than about 80%, less than about 70%, less than about 60%, less than about 50%, less than about 40%, less than about 20%, less than about 10%) of energy impinging thereon at wavelength λ_{s3} . Reflectors 950 and 960 form a resonance cavity 970 in fiber 705 for energy at wavelength λ_{s3} .

With this arrangement, energy at λ_p generally propagates in fiber 705 as described above. In addition energy at wavelengths λ_{s1} , λ_{s1}' and λ_{s2}' generally is formed and propagates through fiber 705 as described above. As energy at wavelength λ_{s2}' propagates through section 730 of fiber 705 (e.g., in the region overlapping cavities 870 and 970), it interacts with the Raman active material of section 730 of fiber 705 to create energy at wavelength λ_{s3} . Energy at wavelength λ_{s3} in cavity 970 that is propagating in the reverse direction is reflected by reflector 950 and then it propagates through fiber 705 in the forward direction. Energy at wavelength λ_{s3} propagating in cavity 970 in the forward direction impinges on reflector 960. Some of the energy at λ_{s3} impinging on reflector 960 is reflected by reflector 960 and then propagates through cavity 970 in the reverse direction, and some of the energy at λ_{s3} impinging on reflector 960 passes through reflector 960 and exits fiber 705 (e.g., at end 715). It is to be noted that, in this embodiment, λ_p directly pumps only λ_{s1} , λ_{s1}' is directly pumped only by λ_{s1} , λ_{s2}' is directly pumped only by λ_{s1}' , and λ_{s3}' is directly pumped only by λ_{s2}' .

Resonance cavities 740 and 770 are linked cavities, resonance cavities 770 and 870 are linked cavities, and resonance cavities 870 and 970 are linked cavities.

Although optical fibers with coupled segments having certain arrangements of splice points and reflectors have been described, the invention is not limited to such arrangements. In general, the splice points and reflectors can be arranged as appropriate to achieve one or more desired output intensities at one or more output wavelengths. As an example, with reference to Fig. 7, splice point 710 can optionally

be between reflectors 725 and 750 or between reflectors 735 and 760. As another example, with reference to Fig. 8, splice point 710 can optionally be between reflectors 725 and 750, between reflectors 735 and 850, between reflectors 850 and 760 or between reflectors 760 and 860. In a further example, with reference to Fig. 9, splice point 710 can optionally be between reflectors 725 and 750, between reflectors 735 and 850, between reflectors 850 and 760, between reflectors 760 and 950, between reflectors 950 and 860 or between reflectors 960 and 860. Typically, the reflectors are arranged so that so that the resonance cavity for energy at a particular wavelength λ_{sn} overlaps only with two resonance cavities (see discussion above). Moreover, it is to be understood that the number of resonance cavities, or portions of resonance cavities, in a particular segment of fiber can be varied as desired.

In addition, while systems containing an optical fiber with two segments of material have been disclosed, optical fibers having different numbers of segments can also be used. In general, the optical fiber can have N segments, where N is an integer greater than or equal to one. For example, the optical fiber can include more than two segments of material having the same or different Raman active material(s) (e.g., three segments, four segments, five segments, six segments, seven segments, eight segments, nine segments, 10 segments, etc.). In general, each section of the optical fiber can have a gain medium with an Raman active material which can be the same or different than the Raman active material in the gain medium of the neighboring section(s) of the fiber. In some embodiments, all sections of the optical fiber have a gain medium with the same Raman active material. In certain embodiments, all sections of the optical fiber have a gain medium with a different Raman active material than the Raman active material in the gain medium of the other sections. In some embodiments the Raman active material in the gain medium of the other sections can alternate. For example, a three-section optical fiber can be formed in which the Raman active material of the gain medium of the first and third sections is the same, and in which the Raman active material in the gain medium in the middle section is different. Other arrangements are contemplated.

Furthermore, while Raman fiber lasers and Raman fiber laser systems have been described in which sections of the optical fiber are spliced together, the invention is not limited in this sense. Generally, the sections of the fiber are coupled together so that energy can propagate therebetween. Typically, the sections of fiber are contiguous. For

example, in some embodiments, two neighboring sections of the optical fiber can be connected by a lens (e.g., a Green lens). Optionally, free-space optics can be used to couple one or more segments of fiber.

Fig. 8 is a schematic view of an embodiment of a fiber amplifier system 11000 in which a Raman fiber laser system 1105 that outputs energy at four wavelengths ($\lambda_1, \lambda_2, \lambda_3, \lambda_4$) is used to amplify the signals propagating along fibers 1122, 1124, 1126, and 1128 respectively. These output wavelengths exit system 1105 and enter a fiber 1108. Fiber 1108 is coupled to a splitter 1110, which couples a portion of the output energy at each wavelength ($\lambda_1, \lambda_2, \lambda_3, \lambda_4$) into fibers 1112, 1114, 1116, and 1118. The pump energy at each wavelength in each fiber 1112, 1114, 1116, and 1118 is coupled into fibers 1122, 1124, 1126, and 1128 respectively, via couplers 1132, 1134, 1136, and 1138 respectively. At least a portion of each of fibers 1122, 1124, 1126, and 1128 contain a gain medium that has a Raman active material. In fibers 1122, 1124, 1126, and 1128 the input signals interact with the pump energy from fibers 1112, 1114, 1116, and 1118, respectively and are amplified by stimulated Raman scattering.

Of course such a system is not limited to amplification of signals in four fibers, or amplification by four wavelengths. In general, a Raman fiber laser system with N output wavelengths, where N is an integer greater than or equal to one (e.g., one, two, three, four, five, six, seven, eight, nine, 10, etc.) can be used to amplify the signal in M different fibers, where M is an integer greater than or equal to one (e.g., one, two, three, four, five, six, seven, eight, nine, 10, etc.). In certain embodiments, M can be, for example, on the order of one hundred or more. In some embodiments, all the fibers in which the signals are amplified by the Raman fiber laser may be bound together in a single or several cables running in parallel (e.g., an under water fiber optic and/or ultra long haul applications).

Figure 9 depicts an embodiment of a fiber amplifier system 12000. System 12000 utilizes four Raman fiber laser systems 1210, 1220, 1230, and 1240, each system emitting energy at an output wavelength that exits systems 1210, 1220, 1230, and 1240 through fibers 1250, 1260, 1270, and 1280, respectively. The output energy from each laser 1210, 1220, 1230, and 1240, is coupled into at least one of the fibers 1112, 1114, 1116, and 1118 via a cross-coupler (e.g., a WDM) 1290. In some embodiments, a portion of output energy at each wavelength generated by each laser system 1210, 1220, 1230, and 1240 is coupled into each fiber 1112, 1114, 1116, and 1118,

respectively via coupler 1290. The pump energy at each wavelength in each fiber 1112, 1114, 1116, and 1118 is coupled into fibers 1122, 1124, 1126, and 1128 respectively, via coupler 1132, 1134, 1136, and 1138 respectively. At least a portion of fibers 1122, 1124, 1126, and 1128 contain a gain medium that has a Raman active material. In fibers
5 1122, 1124, 1126, and 1128 the input signals interact with the pump energy and are amplified by stimulated Raman scattering.

Such a system 12000 is not limited to four lasers or four fibers. Any number of lasers may amplify the signal in any number of fibers. Moreover, a given fiber laser system can output more than one wavelength, which can be coupled into one or more
10 fibers.

A further example of a fiber laser system 13000 is depicted schematically in Figure 10. System 13000 includes a pump laser 1310 (e.g., a semiconductor diode laser) that is connected to a coupler 1350 via fibers 1320, 1330 and 1340. Combiner 1350 is connected to a fiber laser 1370 (e.g., a Ytterbium-doped double clad fiber) via a
15 coupler 1360. Laser 1370 is in turn connected to Raman a fiber laser 1390 (e.g., a Raman fiber laser having the structure described herein) via a coupler 1380, and a laser 1390 is connected to an output cascade 1510 via fiber a coupler 1400. In certain embodiments, laser 1390 and output cascade 1510 are integrated in a single unit.

During operation, energy at wavelength Λ_p is generated by pump laser 1310 and
20 propagates along fibers 1320, 1330, and 1340 and is coupled into fiber laser 1370 via combiner 1350 and coupler 1360. The energy at Λ_p is converted by laser 1370 into energy at λ_p . Energy at λ_p exits laser 1370, propagates along coupler 1380 and is coupled into Raman fiber laser 1390. Energy at wavelength λ_p is converted to energy at one or more longer wavelengths. The energy at these wavelengths is coupled into
25 output cascade 1510 by fiber 1400. Cascade 1510 optionally includes variable output couplers that can be dynamically adjusted to regulate the amount of energy allowed to exit system 13000 at desired wavelengths.

While certain embodiments have been described, the invention is not limited to these embodiments. For example, one or more sections of an optical fiber can be
30 substantially devoid of a gain medium having a Raman active material. As a further example, the reflectors need not be in the form of fiber Bragg gratings. For example, one or more of the reflectors can be a loop mirror, or one or more reflectors can be in the form of a coated mirror (e.g., a coated mirror at one or both ends of a section of

optical fiber). As another example, the suppressor(s) need not be in the form of LPG(s). For example, one or more of the suppressors can be in the form of gratings (e.g., short period gratings, slanted gratings, etc.) that are substantially non-perpendicular to the length of the fiber along which energy propagates. In these
5 embodiments, the angle and/or period of the gratings can be selected to scatter one or more wavelengths of interest (e.g., one or more higher order Raman Stokes shift wavelengths). As an additional example, the type of laser used for pumping can be varied. Examples of lasers that can be used include semiconductor diode lasers (e.g., high power semiconductor diode lasers), double clad doped fiber lasers, conventional
10 free space coupled lasers, and the like. As another example, various types of optical fibers can be used, including, for example, double clad optical fibers and polarization maintaining optical fibers. Furthermore, the optical fibers can be formed of, for example, silica based materials (e.g., fused silica based) or fluoride-based materials. As yet another example, the relative and/or absolute lengths of one or more of the
15 sections of the optical fiber can be varied based upon the intended use of the Raman fiber laser.

Moreover, while the fibers and systems have been described as Raman fiber lasers and Raman fiber laser systems, those skilled in the art will appreciate that the general concepts described can be extended to provide amplifiers and amplifier
20 systems. Generally, a fiber amplifier provides gain for energy at a wavelength or wavelength range of interest without the use of a resonance cavity (e.g., without a resonator) or with an optical cavity operating below resonance threshold. Fig. 11 is a schematic view of an embodiment of a fiber amplifier system 10000 in which a fiber 1050 is used as a signal amplifier. Fiber 1050 can be formed of multiple segments of
25 fiber or a single segment of fiber. To operate at below resonance threshold, for example, one or more of the reflectors can be removed from fiber 1050 and/or the reflectivity of one or more of the reflectors can be reduced. An input signal enters system 10000 via fiber 1005 (the reflectors can be, for example, otherwise arranged as described above). Energy source 1060 emits a pump signal 1070. The input signal in
30 fiber 1005 and pump signal 1070 are coupled into fiber 1050 via coupler 1080. Such couplers are known to those skilled in the art. Pump signal 1070 interacts with the Raman active material(s) in the sections of fiber 1050, and the input signal is amplified. A device 1090 (e.g., a WDM coupler) separates the amplified input signal from the

Stokes shifted pump signal so that the Stokes shifted pump signal travels along fiber 1015, and the amplified input signal travels along fiber 1025. While Fig. 13 shows one embodiment of fiber 1050 in a fiber amplifier system, other fiber amplifier systems in which fiber 1050 can be used will be apparent to those of skill in the art.

5 Furthermore, while the foregoing discussion has been with respect to linked resonance cavities, the invention is not so limited. In certain embodiments, the systems can be formed of a hybrid of linked and nested resonance cavities. Nested resonance cavities refer to resonance cavities in which one resonance cavity is entirely contained within another resonance cavity. For example, Fig. 12 shows a system 12000 including
10 an optical fiber 110, a pair of reflectors 12010 and 12020 (which reflect substantially all energy at wavelength λ_{s1}), a pair of reflectors 12030 and 12040 (which reflect substantially all energy at wavelength λ_{s2}), a pair of reflectors 12050 and 12060 (which reflect substantially all energy at wavelength λ_{s3}), a pair of reflectors 12070 and 12080 (which reflect substantially all energy at wavelength λ_{s4}), and a pair of reflectors 12090
15 and 12100 (which reflect substantially all energy at wavelength λ_{s5}), where λ_{sn} is determined as described above. With this configuration, reflectors 12030 and 12040 form a resonance cavity 12110 that is nested within a resonance cavity 12120 formed by reflectors 12010 and 12020, and reflectors 12070 and 12080 form a resonance cavity 12140 that is nested within a resonance cavity 12130 formed by reflectors 12090 and
20 12100. In addition, reflectors 12050 and 12060 form a resonance cavity 12150. Resonance cavity 12150 is linked with resonance cavity 12110, and resonance cavity 12150 is linked with resonance cavity 12120. Resonance cavity 12150 is linked with resonance cavity 12130, and resonance cavity 12150 is linked with resonance cavity 12140.

25 Other embodiments are in the claims.

WHAT IS CLAIMED IS:

1. A fiber, comprising:

an optical fiber containing a gain medium having a Raman active material with a Raman gain spectrum, the optical fiber being configured to receive energy at a

5 wavelength λ_p ; and

at least three pairs of reflectors disposed in the optical fiber, each pair of reflectors forming a resonance cavity with a resonance frequency, each resonance cavity having an index, the index of each resonance cavity being different than the index of the other resonance cavities,

10 wherein, for a resonance cavity having an index with a value M, M being an integer having a value of at least one, the resonance cavity has a resonance frequency (c/λ_{sm}) , where

$$\lambda_{sm}^{-1} = \lambda_p^{-1} - \sum_M \lambda_{rm}^{-1}$$

15

where (c/λ_{rm}) is a frequency within the Raman gain spectrum of the Raman active material contained in the gain medium and c is the speed of light, and, for a resonance cavity having an index with a value N, N being an integer having a value of at least two, the resonance cavity has a resonance frequency (c/λ_{sn}) , the resonance

20 cavity having the index with the value N overlapping only with a resonance cavity having a resonance frequency $(c/\lambda_{s(n-1)})$ and with a resonance cavity having a resonance frequency $(c/\lambda_{s(n+1)})$ with the caveat that the resonance cavity having the highest value for N overlaps with at most one other resonance cavity.

25 2. The fiber of claim 1, wherein the optical fiber comprises three pairs of reflectors.

3. The fiber of claim 1, wherein the optical fiber comprises four pairs of reflectors.

30

4. The fiber of claim 1, wherein the optical fiber comprises five pairs of reflectors.

5. The fiber of claim 1, wherein the optical fiber comprises six pairs of reflectors.

5 6. The fiber of claim 1, wherein the optical fiber comprises seven pairs of reflectors.

7. The fiber of claim 1, wherein the optical fiber comprises eight pairs of reflectors.

10

8. The fiber of claim 1, wherein the optical fiber comprises nine pairs of reflectors.

9. The fiber of claim 1, wherein the optical fiber comprises 10 pairs of
15 reflectors.

10. The fiber of claim 1, wherein the optical fiber comprises greater than 10 pairs of reflectors.

20 11. The fiber of claim 1, wherein at least one pair of reflectors has a first reflector and a second reflector, the first reflector being disposed in the optical fiber closer to a point where energy at the wavelength λ_p enters the optical fiber than the second reflector, the second reflector being configured to reflect only a portion of energy impinging thereon at the resonance frequency for the resonance cavity formed
25 by the at least one pair of reflectors.

12. The fiber of claim 11, wherein the first reflector is configured to reflect substantially all energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

30

13. The fiber of claim 11, wherein the second reflector is configured to reflect less than 98% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

14. The fiber of claim 11, wherein the second reflector is configured to reflect less than 95% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

5

15. The fiber of claim 11, wherein the second reflector is configured to reflect less than 90% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

10

16. The fiber of claim 11, wherein the second reflector is configured to reflect less than 75% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

17. The fiber of claim 11, wherein the second reflector is configured to
15 reflect less than 60% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

18. The fiber of claim 11, wherein the second reflector is configured to
20 reflect less than 50% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

19. The fiber of claim 11, wherein the second reflector is configured to
reflect less than 25% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

25

20. The fiber of claim 11, wherein the second reflector is configured to reflect less than 10% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

21. The fiber of claim 11, wherein the amount of energy at the resonance
30 frequency for the resonance cavity that the second reflector is capable of reflecting is variable.

22. The fiber of claim 1, wherein each pair of reflectors has a first reflector and a second reflector, and for each pair of reflectors: the first reflector is disposed in the optical fiber closer to a point where energy at the wavelength λ_p enters the optical fiber than the second reflector and the second reflector is configured to reflect only a
5 portion of energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

23. The fiber of claim 22, wherein the first reflector is configured to reflect substantially all energy impinging thereon at the resonance frequency for the resonance
10 cavity formed by the at least one pair of reflectors.

24. The fiber of claim 22, wherein the second reflector is configured to reflect less than 98% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.
15

25. The fiber of claim 22, wherein the second reflector is configured to reflect less than 95% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

20 26. The fiber of claim 22, wherein the second reflector is configured to reflect less than 90% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

27. The fiber of claim 22, wherein the second reflector is configured to
25 reflect less than 75% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

28. The fiber of claim 22, wherein the second reflector is configured to reflect less than 60% of the energy impinging thereon at the resonance frequency for
30 the resonance cavity formed by the first and second reflectors.

29. The fiber of claim 22, wherein the second reflector is configured to reflect less than 50% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

5 30. The fiber of claim 22, wherein the second reflector is configured to reflect less than 25% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

31. The fiber of claim 22, wherein the second reflector is configured to
10 reflect less than 10% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

32. The fiber of claim 22, wherein the amount of energy at the resonance frequency for the resonance cavity that the second reflector is capable of reflecting is
15 variable.

33. The fiber of claim 1, wherein at least one resonance cavity has a suppressor disposed therein, the suppressor being configured to substantially suppress formation of energy at a frequency (c/λ_x) where

20

$$\lambda_x^{-1} = \lambda_z^{-1} - \lambda_a^{-1},$$

(c/λ_z) is a resonance frequency of the at least one resonance cavity and (c/λ_a) is a frequency in the Raman gain spectrum of the active material in the gain medium in
25 the optical fiber.

34. The fiber of claim 33, wherein the suppressor comprises one or more long period gratings.

30 35. The fiber of claim 1, wherein, for each resonance cavity, the resonance cavity has suppressor disposed therein, the suppressor being configured to substantially suppress formation of energy at a frequency in the Raman gain spectrum of the active material in the gain medium in the optical fiber.

36. The fiber of claim 35, wherein the suppressor comprises one or more long period gratings.

5 37. The fiber of claim 1, wherein one pair of reflectors has first and second reflectors, the first and second reflectors being configured to reflect substantially all energy impinging thereon at the resonance frequency of the corresponding resonance cavity.

10 38. The fiber of claim 1, wherein the at least three pairs of reflectors includes a first pair of reflectors and a second pair of reflectors, the first pair of reflectors having first and second reflectors, the second pair of reflectors having first and second reflectors, the first and second reflectors of the first pair of reflectors being configured to reflect substantially all energy impinging thereon at the resonance
15 frequency of the resonance cavity formed by first pair of reflectors, and the first and second reflectors of the second pair of reflectors being configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the second pair of reflectors.

20 39. The fiber of claim 1, wherein the at least three pairs of reflectors includes a first pair of reflectors, a second pair of reflectors and a third pair of reflectors, the first pair of reflectors having first and second reflectors, the second pair of reflectors having first and second reflectors, the third pair of reflectors having first and second reflectors, the first and second reflectors of the first pair of reflectors being
25 configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the first pair of reflectors, the first and second reflectors of the second pair of reflectors being configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the second pair of reflectors, and the first and second reflectors of the
30 third pair of reflectors being configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the third pair of reflectors.

40. The fiber of claim 1, further comprising an additional reflector disposed in the optical fiber, the additional reflector being configured to at least partially reflect energy impinging thereon at the wavelength λ_p .

5 41. The fiber of claim 1, further comprising an additional reflector disposed in the optical fiber, the additional reflector being configured to reflect substantially all energy impinging thereon at the wavelength λ_p .

42. The fiber of claim 1, wherein at one of the pairs of reflectors comprise
10 pairs of fiber Bragg gratings.

43. The fiber of claim 1, wherein each pair of reflectors comprises a pair of fiber Bragg gratings.

15 44. The fiber of claim 1, wherein the Raman active material comprises a material selected from the group consisting of GeO_2 , P_2O_5 , SiO_2 , B_2O_3 and SiO_xF_y .

45. The fiber of claim 1, wherein the Raman active material is selected from the group consisting of GeO_2 and P_2O_5 .

20

46. A fiber laser system, comprising:
an energy source configured to emit energy at a wavelength λ_p ; and
a fiber, comprising:

25 an optical fiber containing a gain medium having a Raman active material with a Raman gain spectrum, the optical fiber being configured to receive energy from the energy source at the wavelength λ_p ; and

at least three pairs of reflectors disposed in the optical fiber, each pair of reflectors forming a resonance cavity with a resonance frequency, each resonance cavity having an index, the index of each resonance cavity being different than the
30 index of the other resonance cavities,

wherein, for a resonance cavity having an index with a value M , M being an integer having a value of at least one, the resonance cavity has a resonance frequency (c/λ_{sm}) , where

$$\lambda_{sm}^{-1} = \lambda_p^{-1} - \sum_M \lambda_{rm}^{-1}$$

where (c/λ_{rm}) is a frequency within the Raman gain spectrum of the Raman
 5 active material contained in the gain medium and c is the speed of light, and, for a
 resonance cavity having an index with a value N , N being an integer having a value of
 at least two, the resonance cavity has a resonance frequency (c/λ_{sn}) , the resonance
 cavity having the index with the value N overlapping only with a resonance cavity
 having a resonance frequency $(c/\lambda_{s(n-1)})$ and with a resonance cavity having a resonance
 10 frequency $(c/\lambda_{s(n+1)})$ with the caveat that the resonance cavity having the highest value
 for N overlaps with at most one other resonance cavity.

47. The system of claim 46, wherein the energy source comprises a laser.

15 48. The system of claim 46, wherein the energy source is capable of lasing
 at the wavelength λ_p .

49. A fiber, comprising:

an optical fiber containing a gain medium having a Raman active material, the
 20 optical fiber being configured to receive energy at a wavelength λ_p ; and
 at least three pairs of reflectors disposed in the optical fiber, each pair of
 reflectors forming a corresponding resonance cavity with a corresponding resonance
 frequency, the resonance frequency of each resonance cavity being different than the
 resonance frequency of any other cavity,

25 wherein the optical fiber is substantially devoid of a portion containing more
 than two of the resonance cavities.

50. The fiber of claim 49, wherein the optical fiber comprises three pairs of
 reflectors.

30 51. The fiber of claim 49, wherein the optical fiber comprises four pairs of
 reflectors.

52. The fiber of claim 49, wherein the optical fiber comprises five pairs of reflectors.
- 5 53. The fiber of claim 49, wherein the optical fiber comprises six pairs of reflectors.
54. The fiber of claim 49, wherein the optical fiber comprises seven pairs of reflectors.
- 10 55. The fiber of claim 49, wherein the optical fiber comprises eight pairs of reflectors.
56. The fiber of claim 49, wherein the optical fiber comprises nine pairs of reflectors.
- 15 57. The fiber of claim 49, wherein the optical fiber comprises 10 pairs of reflectors.
58. The fiber of claim 49, wherein the optical fiber comprises greater than 10 pairs of reflectors.
- 20 59. The fiber of claim 49, wherein at least one pair of reflectors has a first reflector and a second reflector, the first reflector being disposed in the optical fiber closer to a point where energy at the wavelength λ_p enters the optical fiber than the second reflector, the second reflector being configured to reflect only a portion of energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.
- 30 60. The fiber of claim 59, wherein the first reflector is configured to reflect substantially all impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

61. The fiber of claim 59, wherein the second reflector is configured to reflect less than 98% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

5 62. The fiber of claim 59, wherein the second reflector is configured to reflect less than 95% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

63. The fiber of claim 59, wherein the second reflector is configured to
10 reflect less than 90% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

64. The fiber of claim 59, wherein the second reflector is configured to
15 reflect less than 75% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

65. The fiber of claim 59, wherein the second reflector is configured to
20 reflect less than 60% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

66. The fiber of claim 59, wherein the second reflector is configured to
reflect less than 50% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

25 67. The fiber of claim 59, wherein the second reflector is configured to reflect less than 25% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

68. The fiber of claim 59, wherein the second reflector is configured to
30 reflect less than 10% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the at least one pair of reflectors.

69. The fiber of claim 59, wherein the amount of energy at the resonance frequency for the resonance cavity that the second reflector is capable of reflecting is variable.

5 70. The fiber of claim 49, wherein each pair of reflectors has a first reflector and a second reflector, and for each pair of reflectors: the first reflector is disposed in the optical fiber closer to a point where energy at the wavelength λ_p enters the optical fiber than the second reflector and the second reflector is configured to reflect only a portion of energy impinging thereon at the resonance frequency for the resonance
10 cavity formed by the first and second reflectors.

71. The fiber of claim 70, wherein the first reflector is configured to reflect substantially all energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

15

72. The fiber of claim 70, wherein the second reflector is configured to reflect less than 98% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

20 73. The fiber of claim 70, wherein the second reflector is configured to reflect less than 95% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

74. The fiber of claim 70, wherein the second reflector is configured to
25 reflect less than 90% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

75. The fiber of claim 70, wherein the second reflector is configured to reflect less than 75% of the energy impinging thereon at the resonance frequency for
30 the resonance cavity formed by the first and second reflectors.

76. The fiber of claim 70, wherein the second reflector is configured to reflect less than 60% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

5 77. The fiber of claim 70, wherein the second reflector is configured to reflect less than 50% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

78. The fiber of claim 70, wherein the second reflector is configured to
10 reflect less than 25% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

79. The fiber of claim 70, wherein the second reflector is configured to
15 reflect less than 10% of the energy impinging thereon at the resonance frequency for the resonance cavity formed by the first and second reflectors.

80. The fiber of claim 70, wherein the amount of energy at the resonance
frequency for the resonance cavity that the second reflector is capable of reflecting is
variable.

20

81. The fiber of claim 49, wherein at least one resonance cavity has a
suppressor disposed therein, the suppressor being configured to substantially suppress
formation of energy at a frequency (c/λ_x) where

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$$\lambda_x^{-1} = \lambda_z^{-1} - \lambda_a^{-1},$$

(c/λ_z) is a resonance frequency of the at least one resonance cavity and (c/λ_a) is
a frequency in a Raman gain spectrum of the active material in the gain medium in the
optical fiber.

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82. The fiber of claim 81, wherein the suppressor comprises one or more
long period gratings.

83. The fiber of claim 49, wherein, for each resonance cavity, the resonance cavity has a suppressor disposed therein, the suppressor being configured to substantially suppress formation of energy at a frequency in the Raman gain spectrum of the active material in the gain medium in the optical fiber.

5

84. The fiber of claim 83, wherein the suppressor comprises one or more long period gratings.

85. The fiber of claim 49, wherein one pair of reflectors has first and second
10 reflectors, the first and second reflectors being configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the pair of reflectors.

86. The fiber of claim 49, wherein the at least three pairs of reflectors
15 includes a first pair of reflectors and a second pair of reflectors, the first pair of reflectors having first and second reflectors, the second pair of reflectors having first and second reflectors, the first and second reflectors of the first pair of reflectors being configured to reflect substantially all energy impinging thereon at the resonance
20 frequency of the resonance cavity formed by the first pair of reflectors, and the first and second reflectors of the second pair of reflectors being configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the second pair of reflectors.

87. The fiber of claim 49, wherein the at least three pairs of reflectors
25 includes a first pair of reflectors, a second pair of reflectors and a third pair of reflectors, the first pair of reflectors having first and second reflectors, the second pair of reflectors having first and second reflectors, the third pair of reflectors having first and second reflectors, the first and second reflectors of the first pair of reflectors being configured to reflect substantially all energy impinging thereon at the resonance
30 frequency of the resonance cavity formed by the first pair of reflectors, the first and second reflectors of the second pair of reflectors being configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the second pair of reflectors, and the first and second reflectors of the

third pair of reflectors being configured to reflect substantially all energy impinging thereon at the resonance frequency of the resonance cavity formed by the third pair of reflectors.

5 88. The fiber of claim 49, further comprising an additional reflector disposed in the optical fiber, the additional reflector being configured to at least partially reflect energy impinging thereon at the wavelength λ_p .

 89. The fiber of claim 49, further comprising an additional reflector
10 disposed in the optical fiber, the additional reflector being configured to reflect substantially all energy impinging thereon at the wavelength λ_p .

 90. The fiber of claim 49, wherein at least one pair of reflectors comprise pairs of fiber Bragg gratings.

15

 91. The fiber of claim 49, wherein each pair of reflectors comprises a pair of fiber Bragg gratings.

 92. The fiber of claim 49, wherein the Raman active material comprises a
20 material selected from the group consisting of GeO_2 , P_2O_5 , SiO_2 , B_2O_3 and SiO_xF_y .

 93. The fiber of claim 49, wherein the Raman active material is selected from the group consisting of GeO_2 and P_2O_5 .

25

 94. A fiber laser system, comprising:
 an energy source configured to emit energy at a wavelength λ_p ; and
 a fiber, comprising:

 an optical fiber containing a gain medium having a Raman active material, the optical fiber being configured so that energy emitted by the energy source
30 at the λ_p can be coupled into the optical fiber; and

 at least three pairs of reflectors disposed in the optical fiber, each pair of reflectors forming a corresponding resonance cavity with a corresponding resonance

frequency, the resonance frequency of each resonance cavity being different than the resonance frequency of any other cavity,

wherein the optical fiber is substantially devoid of a portion containing more than two of the resonance cavities.

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95. The system of claim 94, wherein the energy source comprises a laser.

96. The system of claim 94, wherein the energy source is capable of lasing at the wavelength λ_p .

10

97. A fiber, comprising:

an optical fiber containing a plurality of sections including a first section having a gain medium including a first Raman active material and a second section having a gain medium including a second Raman active material, the optical fiber being

15

configured to receive energy at a wavelength λ_p ; and

at least three pairs of reflectors disposed in the optical fiber, each pair of reflectors forming a corresponding resonance cavity with a corresponding resonance frequency,

20

wherein the optical fiber is substantially devoid of a portion containing more than two of the resonance cavities.

98. The fiber of claim 97, wherein the first section of the optical fiber contains at least a first pair of reflectors and the second section of the optical fiber contains a second pair of reflectors different than the first pair of reflectors.

25

99. The fiber of claim 98, wherein the first section of the optical fiber contains a first reflector of a third pair of reflectors different than the first and second pairs of reflectors, and the second section of the optical fiber contains a second reflector of the third pair of reflectors.

30

100. The fiber of claim 97, wherein the first Raman active material is selected from the group consisting of GeO_2 , P_2O_5 , SiO_2 , B_2O_3 and SiO_xF_y .

101. The fiber of claim 100, wherein the second Raman active material is selected from the group consisting of GeO_2 , P_2O_5 , SiO_2 , B_2O_3 and SiO_xF_y .

102. The fiber of claim 97, wherein the first Raman active material comprises
5 P_2O_5 .

103. The fiber of claim 102, wherein the first section of fiber contains one pair of reflectors.

104. The fiber of claim 103, wherein the pair of reflectors contained in the first section of fiber forms a resonance cavity having a resonance frequency (c/λ_1) , where

$$\lambda_1^{-1} = \lambda_p^{-1} - \lambda_a^{-1},$$

15

and (c/λ_a) is a frequency in a Raman gain spectrum of the Raman active material in the gain medium of the first section of the optical fiber.

105. The fiber of any of claims 102-104, wherein the second Raman active
20 material comprises GeO_2 .

106. The fiber of claim 105, wherein the second section of fiber contains two pairs of reflectors.

107. The fiber of claim 106, wherein one of the two pairs of reflectors contained in the second section of the optical fiber forms a resonance cavity has a resonance frequency (c/λ_2) and one of two pairs of reflectors contained in the second section of the optical fiber has a resonance frequency (c/λ_2') , where

30

$$\begin{aligned}\lambda_2^{-1} &= \lambda_p^{-1} - \lambda_b^{-1}, \\ \lambda_2'^{-1} &= \lambda_2^{-1} - \lambda_c^{-1}\end{aligned}$$

and (c/λ_a) and (c/λ_a) is each a frequency in a Raman gain spectrum of the Raman active material in a gain medium of the second section of the optical fiber.

108. The fiber of claim 107, wherein the first section of the optical fiber
5 contains a first reflector of an additional pair of reflectors, and the second section of the optical fiber contains a second reflector of the additional pair of reflectors.

109. The fiber of any of claims 97-101, wherein the second Raman active material comprises GeO_2 .

10

110. The fiber of claim 109, wherein the second section of fiber contains three pairs of reflectors.

111. The fiber of claim 109 or 110, wherein the first Raman active material
15 comprises P_2O_5 .

112. The fiber of claim 111, wherein the first section of the optical fiber contains a first reflector of an additional pair of reflectors, and the second section of the optical fiber contains a second reflector of the additional pair of reflectors.

20

113. The fiber of claim 112, wherein the additional pair of reflectors forms a resonance cavity having a resonance frequency (c/λ_1) , where

$$\lambda_1^{-1} = \lambda_p^{-1} - \lambda_a^{-1},$$

25

and (c/λ_a) is a frequency in a Raman gain spectrum of the Raman active material in the gain medium of the first section of the optical fiber.

114. The fiber of claim 113, wherein the three pairs of reflectors contained in
30 the second section of fiber form a resonance cavity have a resonance frequency of (c/λ_2) , (c/λ_2') , (c/λ_2'') , respectively, where

$$\lambda_2^{-1} = \lambda_1^{-1} - \lambda_b^{-1},$$

$$\lambda_2'^{-1} = \lambda_2^{-1} - \lambda_c^{-1}$$

$$\lambda_{2''}^{-1} = \lambda_2^{-1} - \lambda_d^{-1}$$

- and (c/λ_b) , (c/λ_c) and (c/λ_d) is each a frequency in a Raman gain spectrum of the
 5 Raman active material in the gain medium of the second section of the optical fiber.

115. A fiber laser system, comprising:

an energy source configured to emit energy at a wavelength λ_p ; and
 a fiber, comprising:

- 10 an optical fiber containing a plurality of sections including a first section
 having a gain medium including a first Raman active material and a second section
 having a gain medium including a second Raman active material different than the first
 Raman active material, the optical fiber being configured so that energy emitted by the
 energy source at the λ_p can be coupled into the optical fiber; and

- 15 at least three pairs of reflectors disposed in the optical fiber, each pair of
 reflectors forming a corresponding resonance cavity with a corresponding resonance
 frequency,

wherein the optical fiber is substantially devoid of a portion containing more
 than two of the resonance cavities.

20

116. The system of claim 115, wherein the energy source comprises a laser.

117. The system of claim 115, wherein the energy source is capable of lasing
 at the wavelength λ_p .

25

118. A fiber, comprising:

an optical fiber containing a gain medium having a Raman active material, the
 optical fiber being configured to receive energy at a wavelength λ_p ; and

- a plurality of reflectors disposed in the optical fiber, at least some of the
 30 plurality of reflectors forming resonance cavities in the optical fiber, each resonance
 cavity having a resonance frequency, the resonance frequency of each resonance cavity
 being different than the resonance frequency of any other cavity,

wherein the plurality of reflectors are configured so that when the optical fiber receives energy at the wavelength λ_p , a ratio of an output power at an output wavelength to a power received by the optical fiber at the wavelength λ_p is at least about 20% of a theoretical limit, the output wavelength being different than λ_p .

5

119. The fiber of claim 118, wherein the ratio is at least about 30% of the theoretical limit.

120. The fiber of claim 118, wherein the ratio is at least about 40% of the
10 theoretical limit.

121. The fiber of claim 118, wherein the ratio is at least about 50% of the theoretical limit.

122. The fiber of claim 118, wherein the ratio is at least about 60% of the
15 theoretical limit.

123. The fiber of claim 118, wherein the ratio is at least about 70% of the theoretical limit.

20

124. A fiber, comprising:

an optical fiber containing a gain medium having a Raman active material, the optical fiber being configured to receive energy at a wavelength λ_p ; and

a plurality of reflectors disposed in the optical fiber, at least some of the
25 plurality of reflectors forming resonance cavities in the optical fiber, each resonance cavity having a resonance frequency, the resonance frequency of each resonance cavity being different than the resonance frequency of any other cavity,

wherein the plurality of reflectors are configured so that when the optical fiber receives energy at the wavelength λ_p , a ratio of output power output wavelengths to a
30 power received by the optical fiber at the wavelength λ_p is at least about 20% of a theoretical limit, the output wavelength being different than λ_p .

125. The fiber of claim 124, the ratio is at least about 30% of the theoretical limit.

126. The fiber of claim 124, wherein the ratio is at least about 40% of the
5 theoretical limit.

127. The fiber of claim 124, wherein the ratio is at least about 50% of the theoretical limit.

10 128. The fiber of claim 124, wherein the ratio is at least about 60% of the theoretical limit.

129. The fiber of claim 124, wherein the ratio is at least about 70% of the theoretical limit.

15 130. The fiber of claim 124, wherein the ratio is at least about 80% of the theoretical limit.

131. The fiber of claim 130, wherein the ratio is at least about 90% of the
20 theoretical limit.

132. The fiber of claim 131, wherein the ratio is at least about 95% of the theoretical limit.

25 133. A fiber laser system, comprising:
an energy source configured to emit energy at a wavelength λ_p ; and
a fiber, comprising:
an optical fiber containing a gain medium having a Raman active
material, the optical fiber being configured so that energy emitted by the energy source
30 at the λ_p can be coupled into the optical fiber; and
a plurality of reflectors disposed in the optical fiber, at least some of the
plurality of reflectors forming resonance cavities in the optical fiber, each resonance

cavity having a resonance frequency, the resonance frequency of each resonance cavity being different than the resonance frequency of any other cavity,

wherein the plurality of reflectors are configured so that when the optical fiber receives energy at the wavelength λ_p , a ratio of an output power at an output wavelength to a power received by the optical fiber at the wavelength λ_p is at least about 20% of a theoretical limit, the output wavelength being different than λ_p .

134. The system of claim 133, wherein the energy source comprises a laser.

135. The system of claim 133, wherein the energy source is capable of lasing at the wavelength λ_p .

136. A fiber laser system, comprising:

an energy source configured to emit energy at a wavelength λ_p ; and

a fiber, comprising:

an optical fiber containing a gain medium having a Raman active material, the optical fiber being configured so that energy emitted by the energy source at the λ_p can be coupled into the optical fiber; and

a plurality of reflectors disposed in the optical fiber, at least some of the plurality of reflectors forming resonance cavities in the optical fiber, each resonance cavity having a resonance frequency, the resonance frequency of each resonance cavity being different than the resonance frequency of any other cavity,

wherein the plurality of reflectors are configured so that when the optical fiber receives energy at the wavelength λ_p , a ratio of a total output power at output wavelengths to a power of the energy received by the optical fiber at the wavelength λ_p is at least about 20% of a theoretical limit, each output wavelength being different than λ_p .

137. The system of claim 136, wherein the energy source comprises a laser.

138. The system of claim 136, wherein the energy source is capable of lasing at the wavelength λ_p .

139. A fiber, comprising:
an optical fiber containing a plurality of segments; and
at least three pairs of reflectors disposed in the optical fiber, each pair of
reflectors forming a resonance cavity with a resonance frequency, each resonance
5 cavity having an index, the index of each resonance cavity being different than the
index of the other resonance cavities,
wherein, for at least one resonance cavity, the at least one resonance cavity
overlaps with only two resonance cavities, one of the two resonance cavities having a
resonance frequency that is one Raman Stokes shift higher than a resonance frequency
10 of the at least one cavity, and the other of the two resonance cavities having a
resonance frequency that is one Raman Stokes shift lower than the resonance frequency
of the at least one cavity.

140. The fiber of claim 97, wherein the first and second Raman active
15 materials are different Raman active materials.

141. The fiber of claim 97, wherein the first and second Raman active
materials are the same Raman active material.

20 142. A system, comprising:
a fiber according to any of claims 1-45, 49-93, 97-114, 118-132, 139-141 or
153-156,
a splitter configured so that output energy from the fiber can be coupled into the
splitter; and
25 a plurality of optical fibers configured so that energy output from the splitter
can be coupled into one or more of the plurality of fibers.

143. The system of claim 142, wherein the plurality of fibers includes at least
five fibers.

30 144. The system of claim 142, wherein the plurality of fibers includes at least
25 fibers.

145. The system of claim 142, wherein the plurality of fibers includes at least 50 fibers.

146. The system of claim 142, wherein the plurality of fibers includes at least
5 75 fibers.

147. The system of claim 142, wherein the plurality of fibers includes at least 100 fibers.

10 148. The system of claim 142, wherein the plurality of fibers includes at least 150 fibers.

149. The system of claim 142, wherein the plurality of fibers includes at least 200 fibers.

15 150. The system of claim 142, wherein the plurality of fibers includes at least 500 fibers.

151. A system, comprising:
20 a pump laser;
a fiber laser coupled to the pump laser so that energy output by the pump laser can be coupled into the fiber laser; and
a fiber according to any of claims 1-45, 49-93, 97-114, 118-132, 139-141 or 153-156, the fiber being coupled to the fiber laser so that energy output by the fiber
25 laser can be coupled into the fiber.

152. The system of claim 151, further comprising an output cascade coupled to the fiber so that energy output by the fiber can be coupled into the output cascade.

30 153. A fiber, comprising:
an optical fiber containing a gain medium having a Raman active material with a Raman gain spectrum, the optical fiber being configured to receive energy at a wavelength λ_p ; and

at least three pairs of reflectors disposed in the optical fiber, each pair of reflectors forming a resonance cavity with a resonance frequency, each resonance cavity having an index, the index of each resonance cavity being different than the index of the other resonance cavities,

- 5 wherein, for a resonance cavity having an index with a value M, M being an integer having a value of at least one, the resonance cavity has a resonance frequency (c/λ_{sm}) , where

$$\lambda_{sm}^{-1} = \lambda_p^{-1} - \sum_M \lambda_{rm}^{-1}$$

10

where (c/λ_{rm}) is a frequency within the Raman gain spectrum of the Raman active material contained in the gain medium and c is the speed of light, and the reflectors are configured so that at least two resonance cavities do not overlap.

- 15 154. The fiber of claim 153, wherein the fiber contains at least two resonance cavities that are nested.

155. The fiber of claim 153, wherein the fiber contains at least two resonance cavities that are linked.

20

156. The fiber of claim 155, wherein the fiber contains at least two resonance cavities that are nested.

- 25 157. A fiber laser system, comprising:
an energy source configured to emit energy at a wavelength λ_p ; and
a fiber, comprising:

an optical fiber containing a gain medium having a Raman active material with a Raman gain spectrum, the optical fiber being configured to receive energy at a wavelength λ_p ; and

- 30 at least three pairs of reflectors disposed in the optical fiber, each pair of reflectors forming a resonance cavity with a resonance frequency, each resonance

cavity having an index, the index of each resonance cavity being different than the index of the other resonance cavities,

wherein, for a resonance cavity having an index with a value M , M being an integer having a value of at least one, the resonance cavity has a resonance frequency
 5 (c/λ_{sm}) , where

$$\lambda_{sm}^{-1} = \lambda_p^{-1} - \sum_M \lambda_{rm}^{-1}$$

where (c/λ_{rm}) is a frequency within the Raman gain spectrum of the Raman
 10 active material contained in the gain medium and c is the speed of light, and the reflectors are configured so that at least two resonance cavities do not overlap.

158. The system of claim 157, wherein the energy source comprises a laser.

15 159. The system of claim 157, wherein the energy source is capable of lasing at the wavelength λ_p .

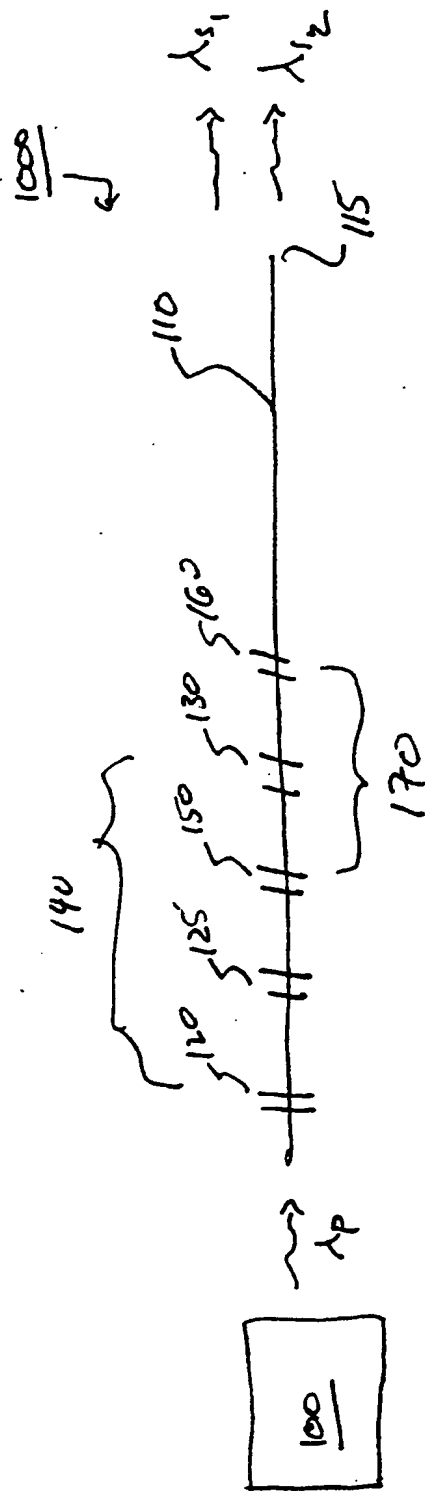


Fig. 1

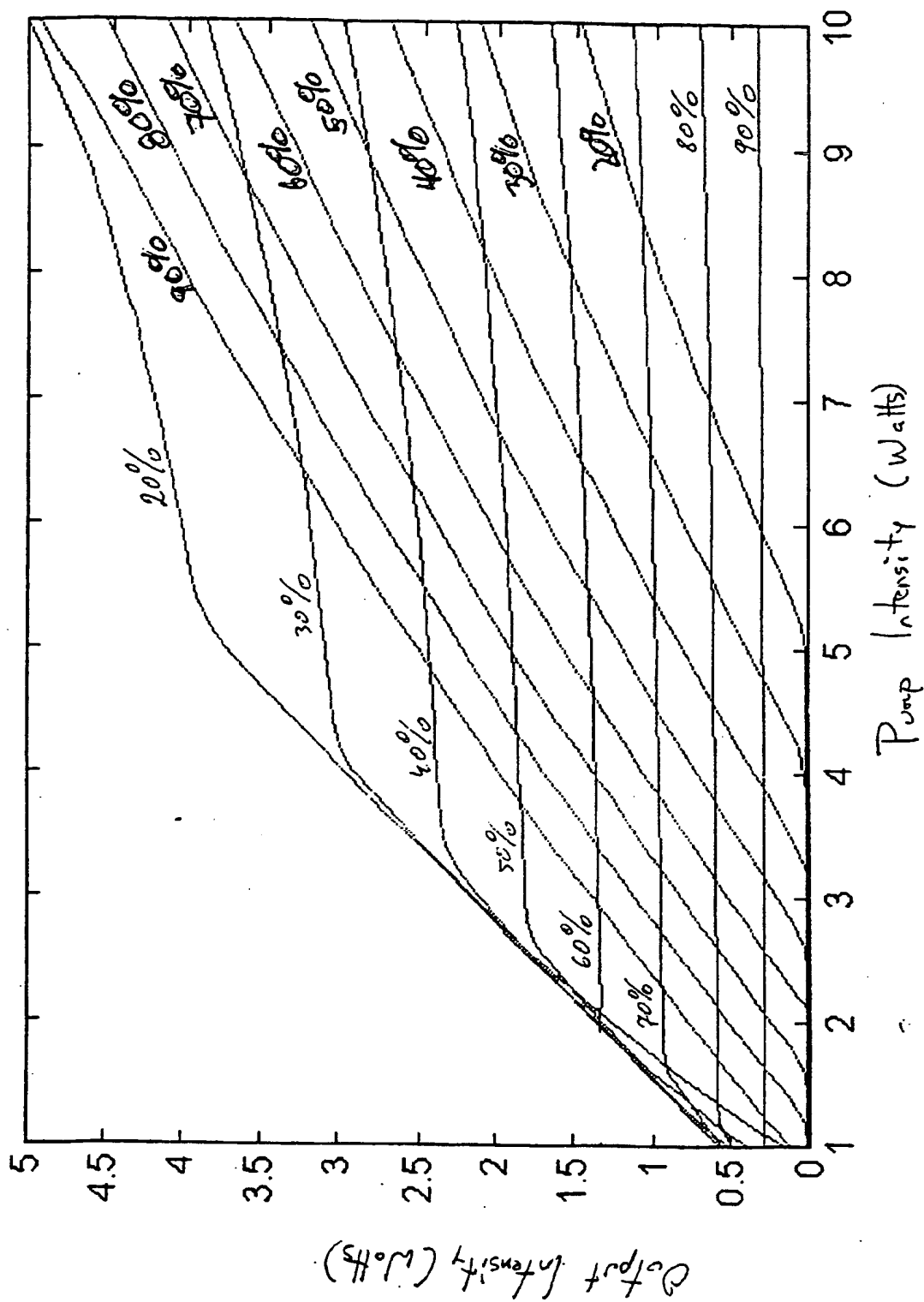


Fig. 2

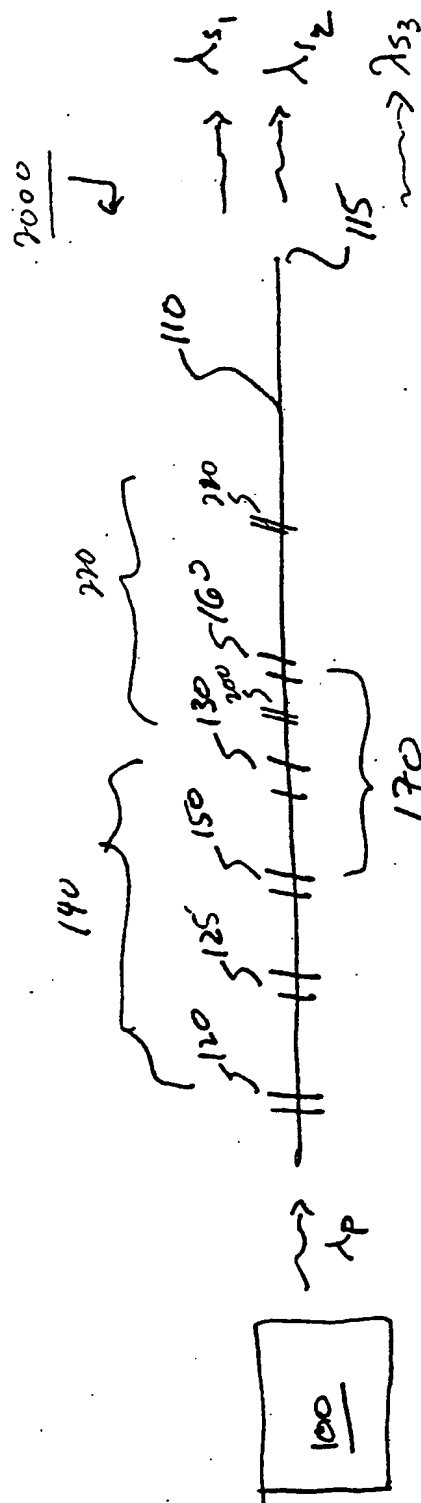


Fig. 3

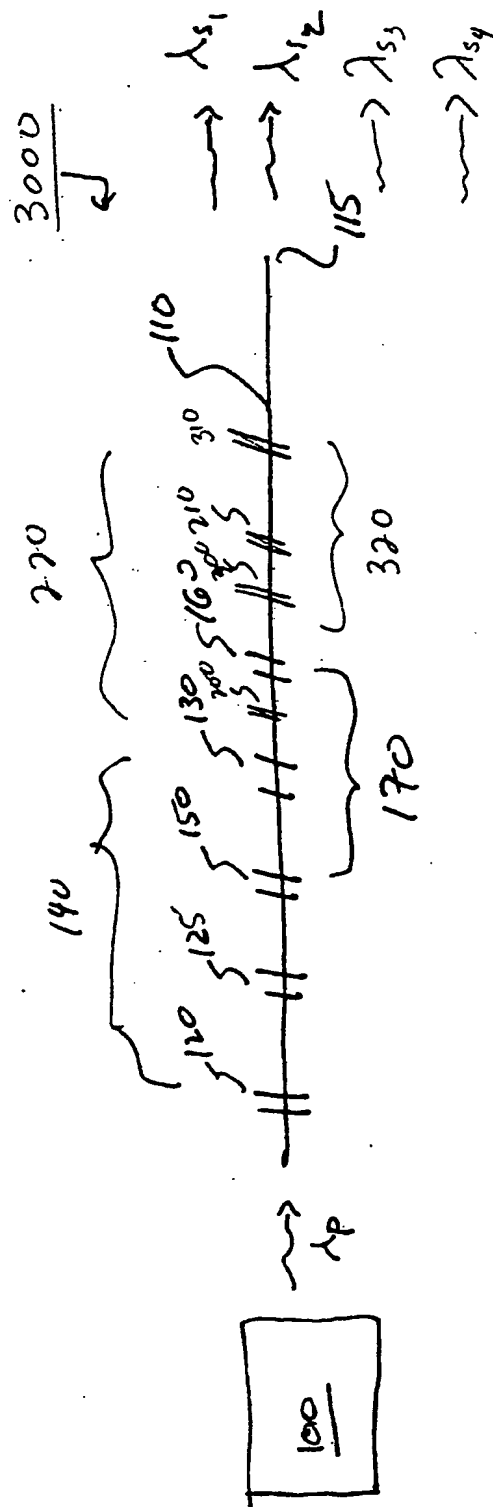


Fig. 4

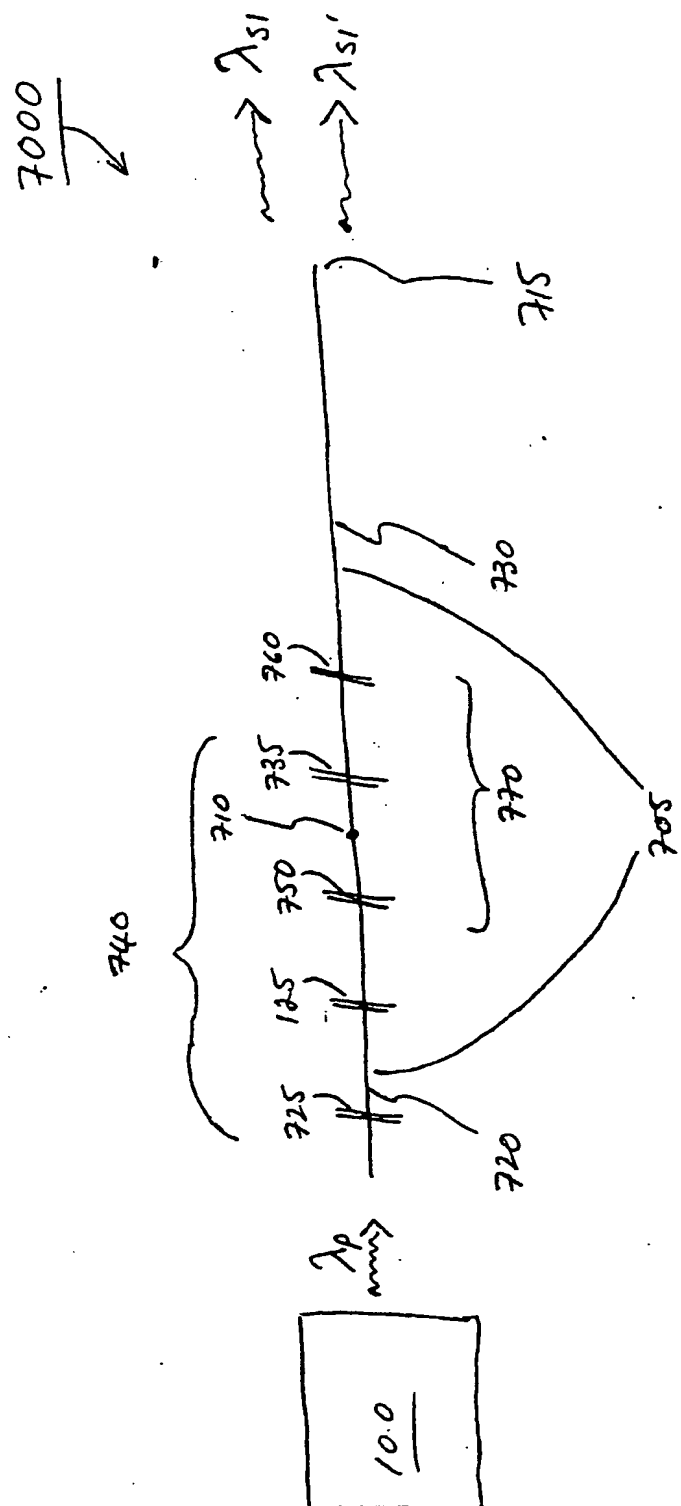


Fig. 5

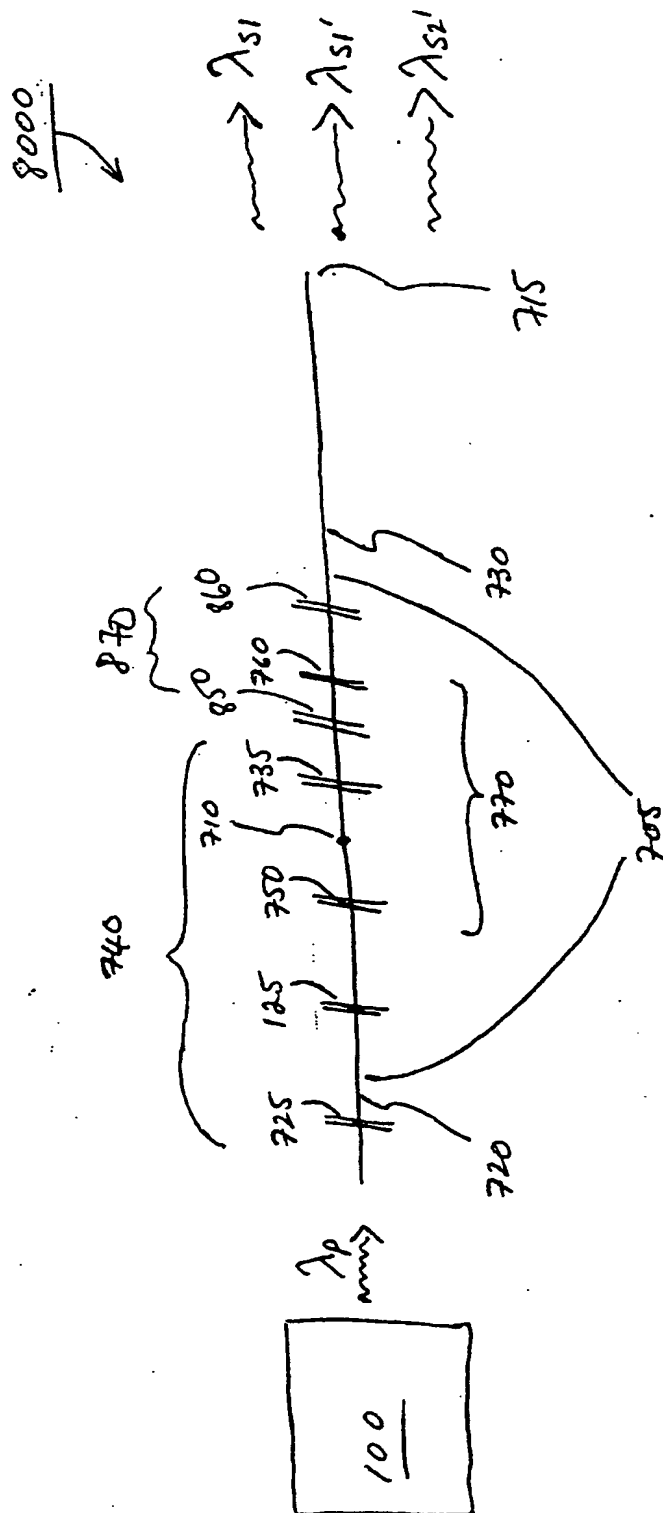


Fig. 6

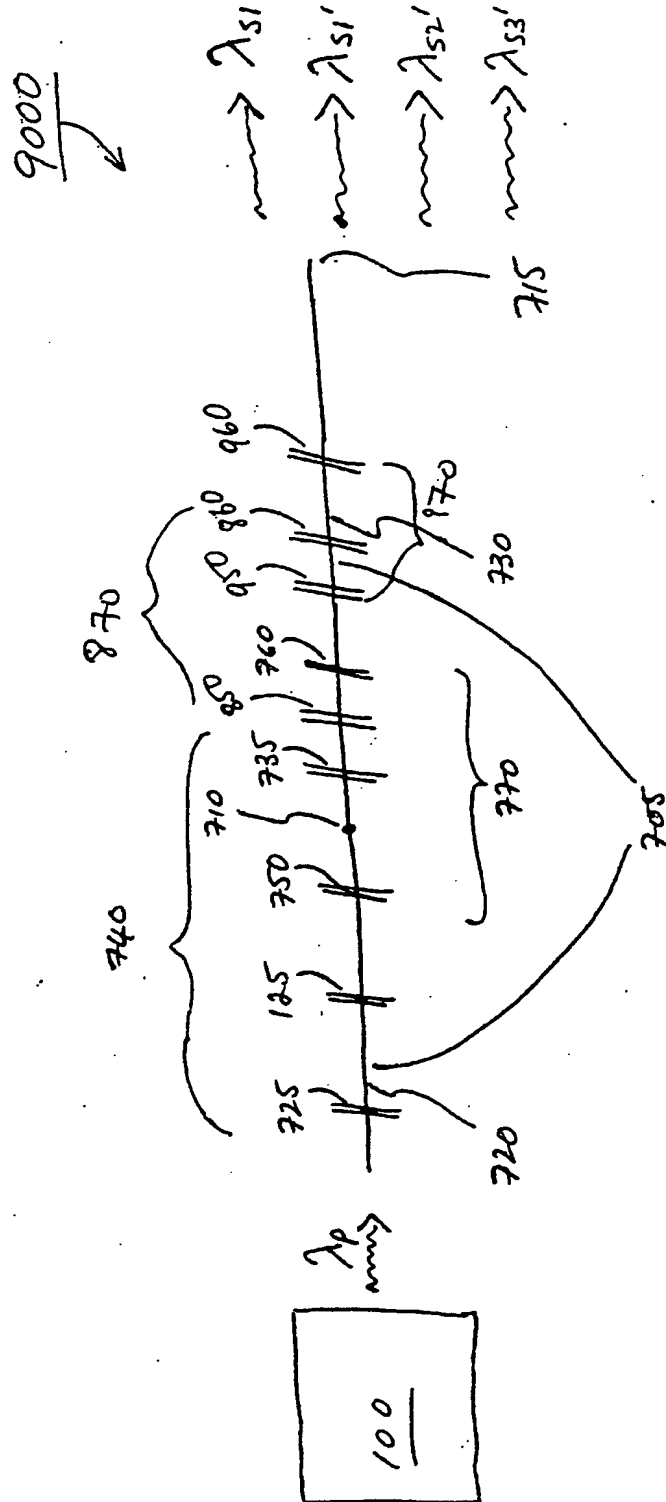


Fig. 7

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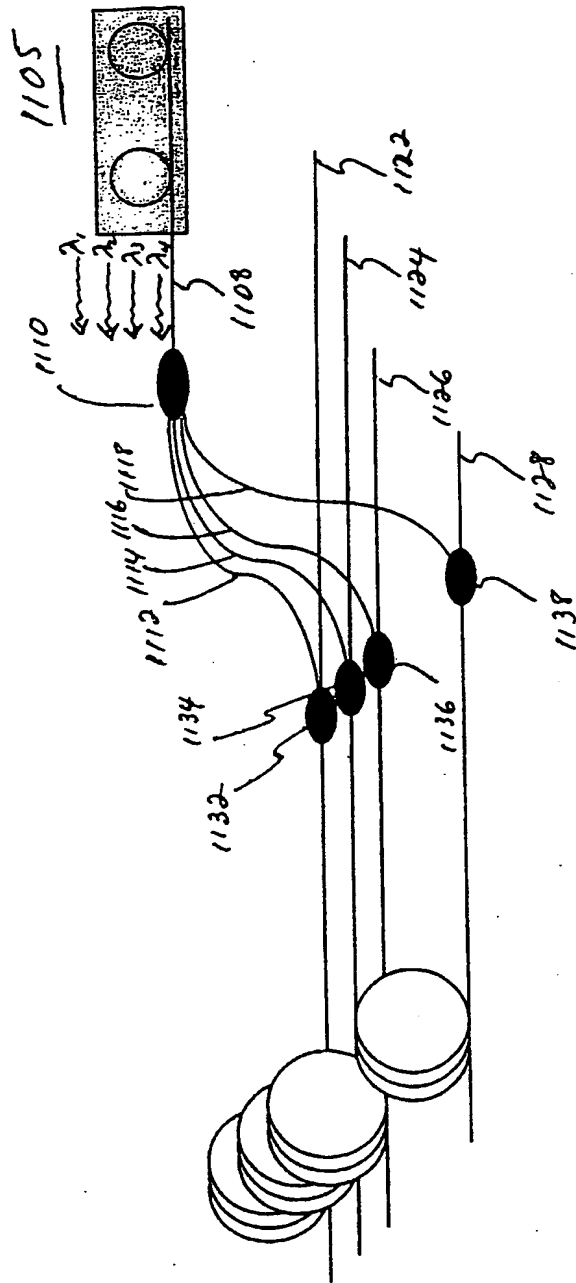


Fig. 8

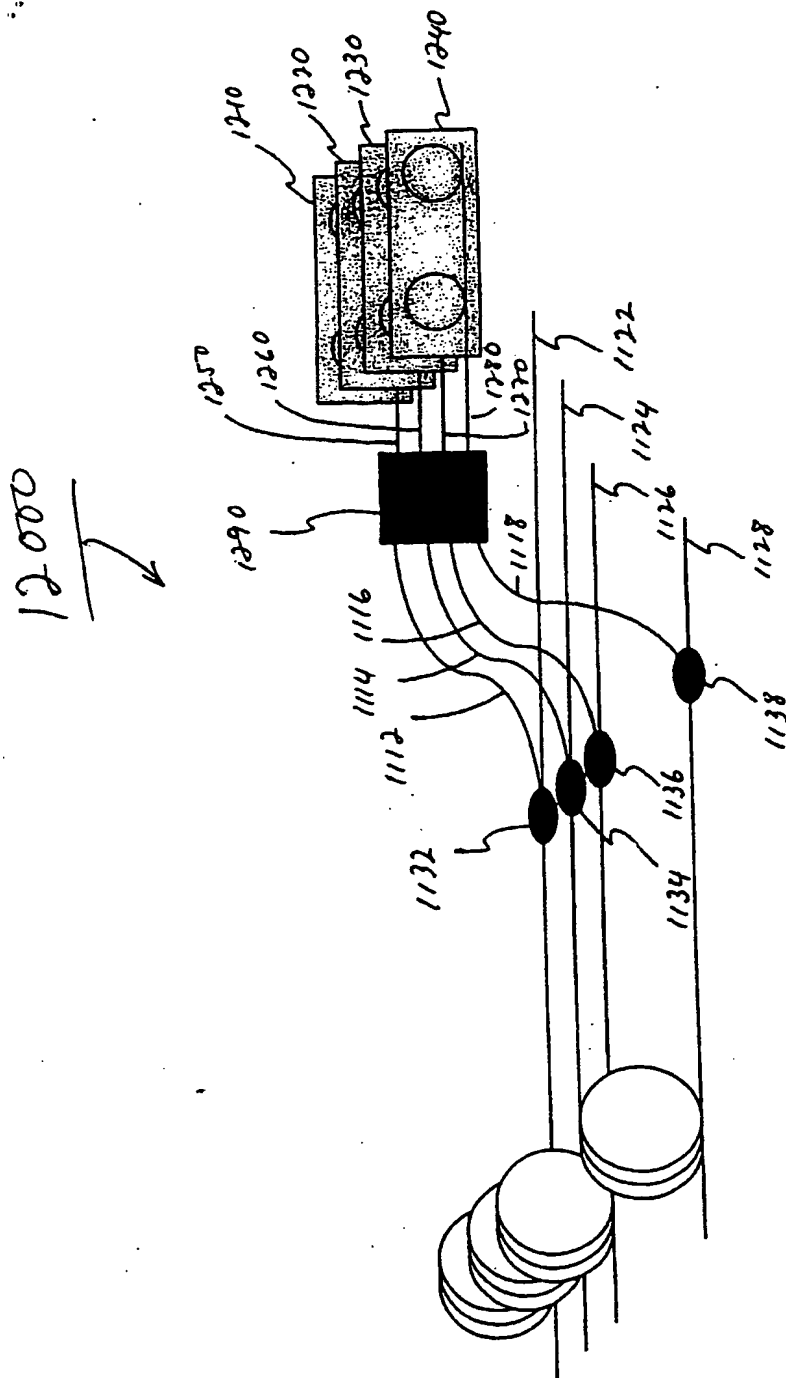


Fig. 9

13 000

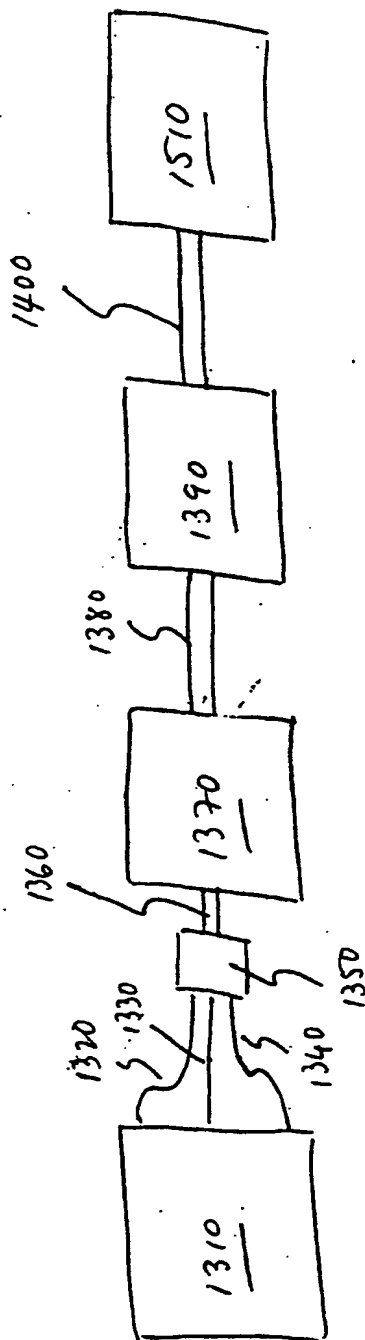


Fig. 10

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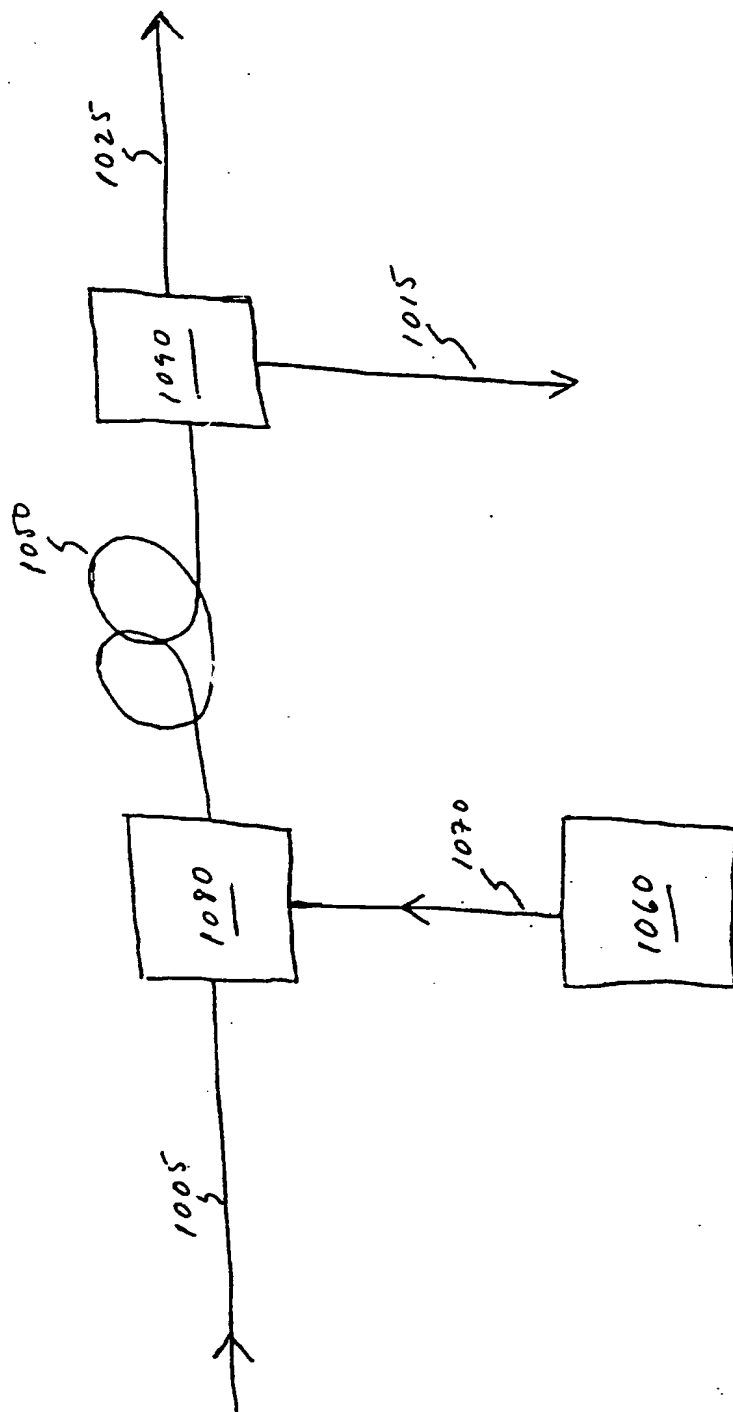


Fig 11

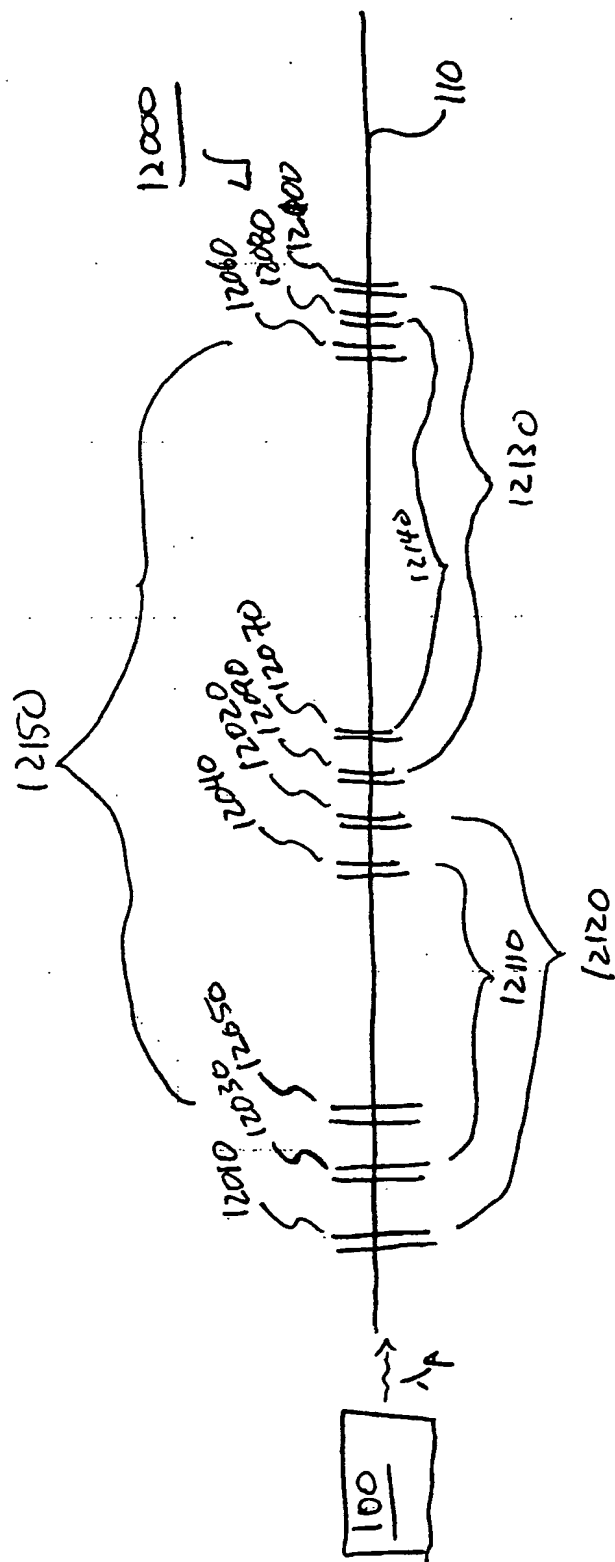


Fig. 12

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
16 January 2003 (16.01.2003)

PCT

(10) International Publication Number
WO 03/005068 A3

(51) International Patent Classification⁷: **G02B 6/02**

(21) International Application Number: PCT/US02/20817

(22) International Filing Date: 1 July 2002 (01.07.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
60/302,603 2 July 2001 (02.07.2001) US

(71) Applicant (*for all designated States except US*): **OPTICAL POWER SYSTEMS INC.** [US/US]; 86 South Street, Hopkington, MA 01748 (US).

(72) Inventors; and

(75) Inventors/Applicants (*for US only*): **DEMIDOV, Andrey, A.** [RU/US]; 1110 Franklin Street, Duxbury, MA 02332 (US). **PO, Hong** [US/US]; 8 Towne Lyne Road, Sherborn, MA 01770 (US).

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU,

CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

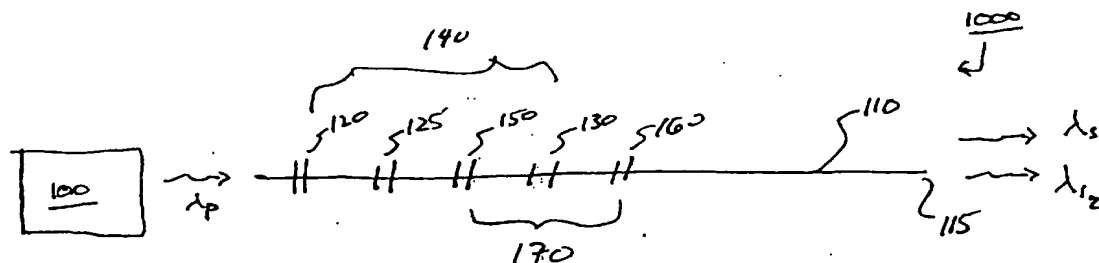
Published:

— with international search report

(88) Date of publication of the international search report:
10 April 2003

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: MULTI-WAVELENGTH OPTICAL FIBER



(57) Abstract: The invention features a fiber that includes an optical fiber (110) containing a gain medium having a Raman active material with a Raman gain spectrum. The optical fiber is configured to receive energy at a wavelength λ_p . The fiber also includes at least three pairs of reflectors (120, 125, 150, 130, 160) disposed in the optical fiber. Each pair of reflectors forms a resonance cavity (140) with a resonance frequency.

WO 03/005068 A3

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US02/20817

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : G02B 6/02

US CL : 385/123

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 385/123; 359/334, 341.1; 372/3,6

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

USPAT, US-PGPUB, EPO, JPO, Derwent

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 6,163,552 A (ENGELBERTH et al.) 19 December 2000 (19.12.2000), Figs. 3, 4, 7, column 2 line 20- column 3 line 44.	1-32, 37-80, 85-141, 151-159
X	US 5,815,518 A (REED et al) 29 September 1998 (29.09.1998), Fig. 3, column 1 line 64- column 2 line 46.	1-12, 22-23, 37-60, 70-71, 85-141, 151-
X	US 5,323,404 A (GRUBB) 21 June 1994 (21.06.1994), Figs. 1-2, column 3 line 10-18, column 3 line 24-56, column 5 line 1-12.	1-12, 22-23, 37-60, 70-71, 85-141, 151-
X,P	US 6,310,899 B1 (JACOBVITZ-VESELKA et al) 30 October 2001 (30.10.2001), see the entire document.	1-12, 22-23, 37-60, 70-71, 85-141, 151-159



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Date of the actual completion of the international search

20 October 2002 (20.10.2002)

Date of mailing of the international search report

17 DEC 2002

Name and mailing address of the ISA/US

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Facsimile No. (703)305-3230

Authorized officer

Sung Pak Macaleso

Telephone No. (703) 308-0956

Form PCT/ISA/210 (second sheet) (July 1998)